

**Effect of irrigation on growth and nitrogen accumulation of
Kabuli chickpea (*Cicer arietinum* L.) and narrow-leafed lupin
(*Lupinus angustifolius* L.)**

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By

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ABSTRACT

Abstract of a thesis submitted in partial fulfilment of the requirements for the degree of Master of Agricultural Science at Lincoln University, Canterbury, New Zealand

Effect of irrigation on growth and nitrogen accumulation of *Kabuli* chickpea (*Cicer arietinum* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.)

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A field experiment was conducted to examine the responses in growth, total dry matter (TDM), seed yield and nitrogen (N) accumulation of *Kabuli* chickpea cv. Principe and narrow-leafed lupin cv. Fest to different irrigation levels and N fertilizer on a Templeton silt loam soil at Lincoln University, Canterbury, New Zealand in 2007/08. The irrigation and fertilizer treatments were double full irrigation, full irrigation, half irrigation and nil irrigation and a control, full irrigation plus 150 kg N ha⁻¹.

There was a 51 % increase in the weighed mean absolute growth rate (WMAGR) by full irrigation over no irrigation. The maximum growth rates (MGR) followed a similar response. The growth rates were not significantly decreased by double irrigation. Further, N fertilizer did not significantly improve crop growth rates. With full irrigation MGRs were 27.6 and 34.1 g m⁻² day⁻¹ for *Kabuli* chickpea and narrow-leafed lupin, respectively.

Seed yields of fully-irrigated crops were trebled over the nil irrigation treatment. With full irrigation, seed yield of chickpea was 326 and that of lupin was 581 g m⁻². Seed yield of the two legumes was reduced by 45 % with double irrigation compared with full irrigation. Nitrogen fertilizer did not increase seed yields in either legume. Increased seed yield with full irrigation was related to increased DM, and crop growth rates, seeds pod⁻¹ and seeds m⁻². Crop harvest index (CHI) was significantly ($P < 0.05$) increased by irrigation and was related to seed yield only in narrow-leafed lupin.

With full irrigation, the crops intercepted more than 95 % of incoming incident radiation at leaf area indices (LAIs), 2.9 and 3 or greater in *Kabuli* chickpea and narrow-leafed lupin, respectively. In contrast, without irrigation the two legumes achieved a maximum fraction of radiation intercepted of less than 90 %. With full irrigation, total intercepted photosynthetically active radiation (PAR) was increased by 28 % and 33 % over no irrigation for *Kabuli* chickpea and narrow-leafed lupin, respectively. Fully-

irrigated *Kabuli* chickpea intercepted a total amount of PAR of 807 MJ m⁻² and fully-irrigated narrow-leafed lupin intercepted 1,042 MJ m⁻². Accumulated DM was strongly related to accumulated intercepted PAR ($R^2 \geq 0.96^{**}$). The final RUE was significantly ($P < 0.001$) increased by irrigation. With full irrigation the final RUE of *Kabuli* chickpea was 1.49 g DM MJ⁻¹ PAR and that of narrow-leafed lupin was 2.17 g DM MJ⁻¹ PAR.

Total N accumulation of *Kabuli* chickpea was not significantly affected by irrigation level. *Kabuli* chickpea total N was increased by 90 % by N fertilizer compared to fully-irrigated *Kabuli* chickpea which produced 17.7 g N m⁻². In contrast, total N accumulated in narrow-leafed lupin was not increased by N fertilizer but was decreased by 75 % with no irrigation and by 25 % with double irrigation (water logging) compared to full irrigation with a total N of 45.9 g m⁻². Total N was highly significantly related to TDM ($R^2 = 0.78^{**}$ for *Kabuli* chickpea and $R^2 = 0.99^{**}$ for narrow-leafed lupin). Nitrogen accumulation efficiency (NAE) of narrow-leafed lupin was not affected by irrigation or by N fertilizer. However, the NAE of *Kabuli* chickpea ranged from 0.013 (full irrigation) to 0.020 (no irrigation) and 0.017 g N g⁻¹ DM (full irrigation with N fertilizer). The N harvest index (NHI) was not affected by irrigation, N fertilizer or legume species. The NHI of *Kabuli* chickpea was 0.50 and that of narrow-leafed lupin was 0.51. The NHI was significantly ($r \geq 0.95^{**}$) related to CHI.

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LIST OF ABBREVIATIONS

Abbreviation	Description	Units
a.i.	active ingredient	g kg^{-1} or g l^{-1}
C	carbon	mg plant^{-1}
CHI	crop harvest index	dimensionless
CV	coefficient of variation	%
DAS	days after sowing	days
DM	dry matter	g m^{-2}
DUR	duration of exponential growth	days
ET	evapotranspiration	mm
F_i	fraction of radiation intercepted	
HI	harvest index	dimensionless
K	extinction coefficient	dimensionless
LAD	leaf area duration	days
LAI	leaf area index	dimensionless
MaxDM	maximum dry matter	g m^{-2}
MGR	maximum growth rate	$\text{g m}^{-2} \text{ day}^{-1}$
N	nitrogen	kg ha^{-1} or g m^{-2}
NAE	nitrogen accumulation efficiency	$\text{g N g}^{-1} \text{ DM}$
NHI	nitrogen harvest index	dimensionless
P	probability	
PAR	photosynthetically active radiation	MJ m^{-2}
r	correlation coefficient	
R^2	coefficient of determination	%
RUE	radiation use efficiency	$\text{g DM MJ}^{-1} \text{ PAR}$
S_a	amount of PAR absorbed	MJ m^{-2}
S_i	amount of total incident PAR	MJ m^{-2}
S.E.M	standard error of mean	
SMC_A	actual soil moisture content	%
SMC_{FC}	soil moisture content at field capacity	%
TDM	total dry matter	g m^{-2}
Ti	fraction of radiation transmitted through the canopy	
WMAGR	weighted mean absolute growth rate	$\text{g m}^{-2} \text{ day}^{-1}$

Chapter 1

General Introduction

The traditional mixed cropping system in New Zealand can be considered to be a sustainable production system; particularly for nitrogen (N) availability (McKenzie *et al.*, 2006). After cropping, paddocks are sown into a pasture with a white clover (*Trifolium repens* L.) component. After a few years, most soils are able to provide sufficient N for successful wheat (*Triticum aestivum* L.) crops (McLaren and Cameron, 1996). However, with production in arable farms in New Zealand intensifying, the duration of the pasture phase has been reduced; thus, the amount of N, derived from biological nitrogen fixation, has also been reduced. This has resulted in increased reliance on N fertilizer and a less sustainable production system (McKenzie *et al.*, 2006).

McKenzie *et al.* (2006) suggested that in New Zealand, agricultural research should not only focus on the economic viability of the farming system but also on the sustainability of the environment. To achieve these two goals, the use of computer simulation models might be of assistance (McKenzie *et al.*, 2006). For instance, Jamieson *et al.* (2006) developed a framework model, Land Use Change and Intensification (LUCI), to quantify production and the potential effect of changing land use on water quality. Jamieson *et al.* (2006) argued that the most appropriate starting point is crop models, which cover the growth, development and N nutrition of each crop in the cropping system.

Grain legumes are often introduced into crop rotations in New Zealand (McKenzie *et al.*, 2006). They are not only cash crops, but they also improve soil fertility (White and Hill, 1999). To improve production and sustainability; to have less reliance on N fertilizer and to enhance legume symbiotic N fixation, it requires research on environmental factors that influence yield and biological N fixation and grain legume N accumulation. This quantitative understanding can assist in the development of legume models which can predict growth, yield and the N contribution of grain legumes to the mixed cropping system.

Irrigation is one of the most limiting factors on East Coast farms in New Zealand (McKenzie *et al.*, 1999). In Canterbury, research results have indicated that irrigation can significantly increase yield of grain legumes; narrow-leafed lupin (*Lupinus angustifolius* L.) (Herbert, 1977), lentil (*Lens culinaris* Medik.) (McKenzie, 1987), field bean (*Vicia faba* L.) (Husain, 1984) and *Kabuli* chickpea (*Cicer arietinum* L.)

(Anwar, 2001). However, these studies did not examine the effect of irrigation on N accumulation. Studies elsewhere have indicated that grain legume N fixation is strongly influenced by water deficit (Sinclair and Serraj, 1995; Serraj *et al.*, 1999).

In irrigated fields, waterlogged conditions may occur due to rainfall after irrigation or from over irrigation. Water logging has also been shown to negatively affect both yield and N accumulation (Greenwood and McNamara, 1987; Bacanamwo and Purcell, 1999). Again, there is little information on this topic available for the Canterbury environment.

A further management tool for improving yield is fertilizer application. There have been no clear-cut results on the effect of additional N fertilizer on grain legume yield (Salvagiotti *et al.*, 2008). McLeod (1987) and Chen *et al.* (1992) reported that there was little or no response to N fertilizer; However, in India, a small amount of N added at sowing has been reported to be beneficial to legume yields (McKenzie *et al.*, 2007). To help reduce dependence on N fertilizer, it is imperative to understand the effect of additional N fertilizer on the yield and N accumulation of grain legumes.

A field study was conducted with different levels of water supply ranging from a water deficit to excess water, with and without N fertilizer, to gain an understanding of the variation in growth, yield and N accumulation of *Kabuli* chickpea and narrow-leafed lupin. This study will provide information which can be used in developing a legume model for predicting the yield and N dynamics of grain legumes in a cropping system. This information will be useful for farmers making decisions on irrigation and fertilizer application for legumes.

The study aims to:

1. Examine the growth and yield response of the two grain legumes to different irrigation levels and N fertilizer application
2. Determine the variation in some physiological mechanisms such as canopy development, radiation interception and radiation use efficiency under various irrigation levels
3. Determine the effect of irrigation on N accumulation in the two grain legumes.

This thesis presents the results of a field experiment carried out during 2007/08 at the Horticultural Research Area, Lincoln University. The thesis is divided into seven chapters. Chapter 2 is a review of the literature. Chapter 3 reports the materials and methods. Chapter 4 describes the effect of different irrigation levels on the growth and

yield *Kabuli* chickpea and narrow-leaved lupin. Canopy development and radiation interception are described in Chapter 5. Chapter 6 describes the effect of irrigation on N accumulation. All the results will be considered together in a general discussion in Chapter 7 where the main conclusions will be presented.

Chapter 2

Literature Review

Introduction

Kabuli chickpea (*Cicer arietinum* L.) is an important pulse crop. It contributes around 14 % to world pulse production, with a total production of 8.2 million t. Chickpea is grown in more than 50 countries, with a growing area of 10.6 million ha in 2006 (FAO, 2008). Leading chickpea producers are India, Turkey, Pakistan, Iran, Canada, Myanmar, Mexico, Ethiopia, Australia, and Morocco. Chickpea seeds consist of fibre, carbohydrates, minerals, protein and vitamins and other phytochemicals, all of which are helpful for human health (Wood and Grusak, 2007). Due to water shortage and other abiotic and biotic constraints seed yield of the crop is low (International Crops Research Institute for the Semi-Arid Tropics, 2006). World average seed yield is 772 kg ha⁻¹. This causes a gap between production and demand. It is estimated that by 2010 the demand for chickpea will be 11.1 million t, 35 % more than current production (International Crops Research Institute for the Semi-Arid Tropics, 2006).

In New Zealand, *Kabuli* chickpea can be considered to be well adapted and it produces relatively high yields. Several studies assessing different chickpea improved lines and cultivars and other agronomic treatments indicated that under experimental conditions chickpea can give seed yield from 2.5 t ha⁻¹ (Hernandez, 1986), 3.4 t ha⁻¹ (McKenzie and Hill, 1995) and 4.7 t ha⁻¹ (Anwar, 2001). With world demand for chickpea increasing, New Zealand farmers may be able to exploit these high yields and develop a new export crop.

Hill (2005) recently concluded that in the absence of alkaloid, lupins are an excellent source, supplemented fibre for humans and protein and energy for animals. Narrow-leafed lupin (*Lupinus angustifolius* L.) seed is 30-35 % of crude protein (White and Hill, 1999) and can be used as an alternative protein source to soybean (*Glycine max* L.). This is particularly so in the European Community, where genetically modified soybeans are less preferable, lupin might have greater potential (Hill, 2005). White and Hill (1999) reported that narrow-leafed lupin has a high yield potential in Canterbury and has produced more than 7 t ha⁻¹ in experiments and 5 t ha⁻¹ in farmer fields. More importantly, lupin has a potential role in improving soil properties and fertility (Ganeshan, 1998).

From the review, *Kabuli* chickpea and narrow-leafed lupin can be potential crops for New Zealand arable farmers. Evaluation of the economic benefit and contribution of the two grain legumes to sustainability in a mixed cropping system should be made using the modelling approach as suggested by McKenzie *et al.* (2006) and Jamieson *et al.* (2006). This approach necessitates research on effect of major environmental factors such as water, on growth, yield, N accumulation and partitioning and the relationship between physiological mechanisms and environmental factors. The aim of this work is to examine the effect of irrigation on the growth, yield and N accumulation of *Kabuli* chickpea and narrow-leafed lupin. This review will focus on these areas; particularly in *Kabuli* chickpea and narrow-leafed lupin but also in other legumes and crops in general.

Effect of water deficit and excess water on plant growth and yield

Framework for describing plant responses

The traditional approach to analysis of plant response in agronomic research was purely based on final yield (Wilson, 1987). Results of this kind of analysis are specifically applicable only to the site or season where the experiment was conducted. It is unlikely that the result can be extrapolated to assess the response of the crop under other conditions (Jamieson *et al.*, 1984; McKenzie *et al.*, 1994). Jamieson *et al.* (1984) reasoned that the limitation of the traditional approach was the exclusion of site and season climatic condition data from the interpretation of the crop response to agronomic treatments. To overcome this limitation, Gallagher *et al.* (1983) suggested an alternative approach which focussed on environmental factors, crop management and crop physiology to gain insight into the mechanisms underlining variation in yield. In this approach, yield is divided into “physiological components” and the effect of environment and management factors on yield variation can be explained by variation in those components (Turner *et al.*, 2001).

On a physiological basis, crop yield can be determined as the product of the total amount of incident solar radiation incoming over the growing season (S), the fraction of radiation intercepted by the crop canopy (F), the efficiency with which radiation is converted into dry matter (DM) and the partitioning of the accumulated DM into harvestable parts (Harvest Index, HI) (Monteith, 1977; Gallagher and Biscoe, 1978; Hay and Porter, 2006).

$$Y = S \times F \times RUE \times HI$$

Equation 2.1

Plant growth analysis is a mathematical approach seeking to interpret the form and function of plant parts which leads to a description of crop performance under different growing conditions (Hunt, 2003). This approach employs mathematical equations to derive growth parameters (relative growth rate, net assimilation rate NAR) and curve fitting. There are several functional approaches including polynomial exponential functions and Richard functions (Richards, 1959), spline functions and ratio (Causton and Venus, 1981).

In a comparative study, Venus and Causton (1979) found that there was no statistically significant difference in the NAR estimated from a fourth-order polynomial and Richards' functions. However, the former indicated that relative growth rate increased at the start and at the end of the growth period with a decline in the middle, which contradicted real biological conditions. The latter produced a relative growth rate trend which was biologically appropriate. Venus and Causton (1979) recommended that Richards' function should be used for plant growth analysis. This function has been widely used. In this work growth analysis was by general logistic function, a type of Richards' function (Gallagher and Robson, 1984). Estimates of the parameters used for this general logistic function are described in detail in Chapter 3, Measurements and calculations.

Dry matter accumulation

Dry matter accumulation of chickpea generally follows a sigmoid curve. At early growth stages, crop growth was very slow and this was followed by a nearly linear increase after flowering and a decline during seed development (Khanna-Chopra and Singha, 1987). This means that most DM accumulation was derived from the late vegetative to the early pod set stage. In *desi* chickpea, Kyei-Boahen *et al.* (2002) reported that while the rate of DM accumulation from the late vegetative stage to podding was $0.06 \text{ g plant}^{-1} \text{ day}^{-1}$, from podding to physiological maturity it was only $0.03 \text{ g plant}^{-1} \text{ day}^{-1}$. As a result, DM accumulation until podding contributed 73 % of total DM. This results is similar to that of McKenzie and Hill (1995). In both *desi* and *Kabuli* chickpea, the highest rate of DM accumulation was between 45 and 75 days after sowing (DAS). Dry matter production declined after this stage. In common bean (*Phaseolus vulgaris* L.), maximum DM was achieved during pod filling (68 DAS). Dry matter production then decreased (Fageria *et al.*, 1997).

This is also the growth pattern of narrow-leafed lupin (Herbert, 1977). Crop growth initiated very slowly and the maximum growth rate was achieved during seed filling. Perry (1975) reported that up to first flowering on the main stem, only 17-25 % of maximum DM had been accumulated. During the first flowering the DM in stems and leaves increased rapidly and reached a maximum with the highest pod dry weight. After this stage vegetative dry weight fell 50 %. The pattern of DM accumulation implied that while there was a decline in DM of stems and leaves with an associated increase in seed weight, the seed DM might be partially derived from the translocation of DM from vegetative parts (Perry, 1975). This mechanism might also occur in chickpea as there was trend for vegetative dry weight to fall during seed development (McKenzie and Hill, 1995). This mechanism has been clarified using carbon (C) labelling techniques (Davies *et al.*, 2000e). Aspect of partitioning will be reviewed later.

While the pattern of DM accumulation shows a sigmoid curve, the growth parameters derived from functional growth analysis are used to characterize cultivars and distinguish different growth responses of cultivars to agronomic treatment, and environmental factors. O'Toole *et al.* (2001) reported a significant difference in relative growth between *desi* and *Kabuli* types. *Desi* types had the highest relative growth rate during vegetative growth whereas *Kabuli* types seemed to have faster growth rates during seed development. In lupins, Herbert (1977) found that white lupin (*Lupinus albus* L.) cv. Ultra had a more rapid decline in relative growth rate than narrow-leafed lupin cv. Unicrop. At 130 DAS while the relative growth rate of Ultra dropped to 0.04 g g⁻¹day⁻¹ in Unicrop was 0.07 g g⁻¹day⁻¹.

Irrigation significantly affects growth parameters. In *Kabuli* chickpea, a fully irrigated crop had a higher weighted mean absolute growth (WMAGR) rate and maximum growth rate than a non-irrigated crop. Maximum growth rates were 17.1 g m⁻² day⁻¹ and 13 g m⁻² day⁻¹ for irrigated and non-irrigated crops, respectively (Anwar *et al.*, 2003b). Similar responses in pinto bean (*Phaseolus vulgaris* L.) were reported by (Dapaah *et al.*, 2000). Herbert (1977) reported that in narrow-leafed lupin cv. WAU11B relative growth rate was significantly higher in irrigated plots than in non-irrigated. This difference was attributed to leaf growth. Irrigated plots had a higher leaf area index (LAI), 7 and longer leaf area duration (LAD) 22 after flowering ended. The LAI and LAD of the non-irrigated plots were 3 and 12, respectively. In soybean, water stress reduced both LAI and crop growth rate (Cox and Jolliff, 1986). As growth strongly depends on the amount of intercepted radiation, which is a direct result of leaf growth (Monteith, 1977), low leaf

growth in non-irrigated plots in the above studies meant plants could not maintain the amount of radiation intercepted, giving a low crop growth rate.

The accumulation of DM in grain legumes is inhibited by waterlogged or flooded conditions. Solaiman *et al.* (2007) reported that in a range of grain legumes, faba bean (*Vicia faba* L.), yellow lupin (*Lupinus luteus* L.), pea (*Pisum sativum* L.), narrow-leafed lupin, chickpea, lentil (*Lens culinaris* Medik.), field pea (*Pisum sativum* L.), transient water logging reduced DM and relative growth rate. Among the legumes tested, lentil and field pea were the most severely affected. Davies *et al.* (2000a) reported that water logging during the vegetative stage decrease crop growth by 81 % and 56 % in narrow-leafed and yellow lupin, respectively. The effect of water logging was more pronounced on root growth than on shoot growth. In soybean after 21 days flooding, DM was reduced by nearly one third (Bacanamwo and Purcell, 1999).

Bacanamwo and Purcell (1999) explained that the reduction of total DM could be attributed to decreased N accumulation, particularly from N fixation. Their explanation was based on the observation that a decrease in N fixation occurred earlier than the a reduction in DM. Shoot N content was significantly reduced; there might have been a reduction in photosynthesis and hence DM (Bacanamwo and Purcell, 1999), since photosynthesis depends on leaf N content (Sinclair and Horie, 1989). However, Davies *et al.* (2000d) indicated that the response of lupins to water logging was influenced more by root than by shoot characteristics. In grafting experiments, there was less reduction in DM in plants with a yellow lupin rootstock than with a narrow-leafed lupin rootstock.

Dry matter partitioning and harvest index

Hay and Porter (2006) suggested that it is imperative to understand the process of partitioning of photo-assimilates in plants. This can be used to explain variation in seed filling that might be limited by translocation of stored material from vegetative parts or from current assimilate synthesis during seed filling. That is the explanation of the effect of source-sink alteration on seed filling. An understanding of this might be ever more important in grain legumes with their indeterminate growth habit. As vegetative growth still continues up to the grain filling stage, there may be a competition between vegetative and reproductive growth for limited assimilates influenced by the growing conditions.

Water deficit has a significant effect on the pattern of DM distribution. In narrow-leafed lupin, French and Turner (1991) reported that while water deficit between 111 and

124 DAS decreased DM accumulation in the main stem by 13 %, the DM of first and second order branches was reduced by 32 and 44 %, respectively. Plants experiencing 8 d of water deficit did not decrease main stem weight but the decreases in second-order branches was 75 % and 66 % for mild and severe transient water deficits, respectively. An altered distribution between vegetative and reproductive parts also occurred. More assimilates were allocated to reproductive parts than to vegetative parts in non-irrigated plants but assimilate distribution to reproductive parts declined in well irrigated plants. This suggested that assimilates were directed to reproductive growth rather than vegetative growth in water deficits which occurred during the reproductive stage (French and Turner, 1991). However, under rainfed, and well watered conditions, Palta *et al.* (2007) reported there was less contribution of remobilized DM from stem to seed as there was no significant relationship between stem dry weight loss and the increase in seed weight. The difference between the two studies might be due to the growing conditions. In Palta *et al.* (2007) crops were grown under rainfed, well watered conditions, thus the crop may not have experienced severe drought; hence, seed growth might have been derived from current assimilates rather than from remobilized storage in the stem.

Using labelling techniques, Davies *et al.* (2000e) found that remobilization of C and N, synthesized before podding, could be added to supplement seed fill in chickpea. The amount of C, in seed, translocated from vegetative parts was 9 % and 13 % for well-water and water stressed plants, respectively. The result implies that the contribution of remobilized C is even more important for plants grown under a water deficit. This result agrees with Khanna-Chopra and Singha (1987) who indicating that 30 % of pod DM was derived from vegetative parts. Water deficit also reduced the amount of remobilized C (Davies *et al.*, 2000e). Nevertheless, Turner *et al.* (2005) emphasized that remobilization of C and N is still important for seed filling of plants experiencing water deficits during final crop growth.

Donald (1962) defined harvest index (HI) as the ratio of economic yield to total biological yield. This concept has been widely used in plant improvement and plant physiology studies and has been applied successfully in cereal improvement (Hay, 1995). This might not be the case in grain legumes. High variability of crop HI results in low seed yields (Ambrose and Hedley, 1984). Hernandez (1986) reported that crop HI of chickpea ranged from 0 % in a wet season to 45 % in a dry season. High variability of HI was attributed to variability of individual plant weight, seed weight, and plant HI, which is a direct result of plant competition in a crop (Ambrose and Hedley, 1984; Moot, 1993).

Moot (1993) proposed a principal axis model as a tool for selecting legumes with weak competition and a high plant HI. This proposed model was confirmed in a range of grain legumes by Ayaz *et al.* (2004).

While plant HI is a useful tool for plant breeding, crop HI is still used for crop modelling purposes for at least two reasons. Firstly, crop HI seems to be stable across growing conditions, including high interplant competition and water stress (Spaeth *et al.*, 1984). Spaeth *et al.* (1984) reported that with high interplant competition and water stress there was high variability in plant size in soybean but crop HIs were relatively constant. Even though some small plants had lower HIs than bigger plants, these small plants did not affect total crop yield and crop HI. Spaeth *et al.* (1984) confirmed that crop HI can be affected by variation in individual plant HIs only at extremely high plant densities. Even under different water deficits, there was no change in crop HI (Ball *et al.*, 2000b). Secondly, the rate of change in HI during grain filling was relatively stable over a wide range of different growing conditions including irrigation; hence seed yield could be quantified by only considering variation in total DM and a constant rate of HI increase (Moot *et al.*, 1996; Bindi *et al.*, 1999).

Total dry matter and seed yield

Irrigation increases the number of reproductive structures, TDM and assimilate partitioning, which contribute to yield component development and higher yields (Anwar, 2001). Anwar (2001) reported that in *Kabuli* chickpea TDM increased by nearly 100 % in fully irrigated plants compared to non-irrigated plants. Similarly, TDM production of mungbean (*Vigna radiata* L.) changed significantly under different irrigation regimes. Irrigation with up to 225 mm of water increased TDM from 2.5 t ha⁻¹ without irrigation to 4.8 t ha⁻¹ (Pannu and Singh, 1993). With narrow-leaved lupin cv. WAU11, Herbert (1977) also reported a positive response to irrigation. The TDM production increased from 1,260 to 1,940 g m⁻² while seed yield increased from 550 to 640 g m⁻². In field bean (*Vicia faba* L.), Newton (1980) reported irrigation increased TDM and yield by 36 % and 41 %, respectively.

Dry matter and seed yield of a narrow-leaved lupin crop were decreased by 50 % and 61 %; respectively, after water logging for 14 days (Davies *et al.*, 2000c). Toker *et al.* (2007) also reported water logging is a major constraint to chickpea production.

Germination, plant growth and plant population were significantly decreased by up to 80 %. Seed yield losses were up to 100 % (Toker *et al.*, 2007).

Seed yield as influenced by source and sink limitation

Yield variation is determined by variation in total DM accumulation and variation in HI (Bindi *et al.*, 1999). Egli (1998) suggested that crop HI (measured at crop maturity) gave less information that can be used for plant improvement. The reason is that HI is a final measurement describing the final product of plant growth at crop maturity. Less insight is gained from this measurement. Hence, information on changes in partitioning to reproductive part during plant growth might be more useful for plant physiologists and breeders, rather than crop HI measured at the end of crop growth. Then, there is the concept of yield limitation by source and sink relationships (Hay and Porter, 2006). The former is the rate of DM accumulation and the latter is the change in HI.

When water stressed, plant growth or DM accumulation rates are significantly reduced, as noted above in the DM accumulation section. There are many reports on yield reductions under water stress (Herbert, 1977; McKenzie, 1987; Dapaah *et al.*, 2000). Husain (1984) reported that in Canterbury, whether field bean crops were sown in spring or autumn, irrigation increased seed yield by increasing total DM. The result is consistent with Ball *et al.* (2000b) who reported that HI was constant across plant population and water regimes and seed yield was related to total DM and crop growth rate. Charles-Edwards (1986) , using data from Pandey *et al.* (1984a; 1984b) , also indicated that in several grain legumes species, subjected to different water regimes, that seeds m^{-2} was significantly related to crop growth rate. Seeds m^{-2} is the main seed yield component and is strongly related to seed yield (Egli, 1998). A similar result was obtained by Guilioni *et al.* (2003). In this irrigation experiment, there was a significant relationship between seed number in pea and plant growth rate. They suggested that peas might change their productive sink proportionally with available assimilate as limited by water deficit. In a shading experiment, Jiang and Egli (1995) also found seeds m^{-2} in soybean was strongly dependent on crop growth rate. Hence, all these results suggest that seed number or seed yield is strongly influenced by the amount of assimilates produced.

Turner *et al.* (2005) held that while drought stress decreases plant growth and photosynthesis, reproductive growth, seed yields might depend more on carbohydrate translocated from vegetative parts. Translocation is also affected by the sink size (Turner *et*

al., 2005). Andriani *et al.* (1991) indicated that increases in seed DM were remobilized from vegetative parts on plant with a high seed number. Comparing different amounts of remobilized C to seed, Davies *et al.* (2000e) also reported that under water stress cultivar Tyson, with higher pod number and seed yield, remobilized more C than cultivar Kaniva with a low pod number and seed yield. In a validation of the model with the assumption that assimilation partitioning is determined by the sink demand, seed number or pod weight, Jeuffroy and Devienne (1995) obtained good agreement between predicted and observed yield. This suggests sink strength can also affect accumulation in seed weight and seed yield.

Seed yield components

Yield component analysis for yield variation has been criticized because of yield component plasticity (Wilson, 1987). Nevertheless seed yield can be influenced by source and sink alteration and these alterations seem to be related to yield components. For instance, seeds m^{-2} is related to crop growth rate (Egli and Zhen-wen, 1991). Seed and pod number can be used to quantify variation in sink capacity (Jeuffroy and Devienne, 1995). Hence, the use of seed yield components might still be a good avenue for describing crop growth and seed yield in a more mechanistic manner. Hay (1995) also indicated that increases in grain number per unit area with invariable grain weight have improved HI and seed yield in most cereal crops.

Pods plant⁻¹

The number of pods $plant^{-1}$ in grain legumes is a key component of seed yield. Pannu and Singh (1993) analysed the contributions of yield components to seed yield using multiple regression. Their results indicate that variation in the number pods $plant^{-1}$ accounted for 97 % of the variation in seed yield. In *Kabuli* chickpea, Anwar (2001) found that although seeds pod^{-1} and plant number changed, the seed yield was significantly related to the number of pods $plant^{-1}$.

This yield component is significantly affected by irrigation. Pods $plant^{-1}$ in field bean increased from 3 to 4 (Newton, 1980). Herbert (1977) reported that pods m^{-2} in narrow-leaved lupin nearly doubled with irrigation. Husain (1984) found that fully irrigated field bean plants had about 40 % more pods $plant^{-1}$ than non-irrigated plants.

Seeds pod⁻¹

There have been results showing different effects of irrigation on seeds pod⁻¹. Newton (1980) reported that irrigation increased the number of field bean seeds pod⁻¹ by 10 %. Similarly, Husain (1984) found increased seeds pod⁻¹ with irrigation. However, in *Kabuli* chickpea, there was no significant effect of irrigation on seeds pod⁻¹ (Anwar, 2001).

In contrast, Herbert (1977), reported that in narrow-leafed lupin seeds pod⁻¹ was lower in fully irrigated plants than in non-irrigated plants. However, in his experiment irrigation still gave a higher seed yield. This could be attributed to more pods plant⁻¹ and a longer LAD. The lower seeds pod⁻¹, particularly on the main stem reflected greater vegetative competition in irrigated plants for branch and pod production. From this review, it is clear that irrigation can increase seed yield through varying different yield components.

100 seed weight

Mean seed weight is another grain legume yield component which is affected by irrigation. Newton (1980) reported that in field bean seed weight increased 5 % with full irrigation. However, in narrow-leafed lupin, Herbert (1977) reported that because of more vegetative competition in irrigated plants the mean seed weight fell 19 %. This agrees with the results of Saxena *et al.* (1990) and Anwar (2001) in *Kabuli* chickpea where the 100 seed weight fell with irrigation. Dapaah *et al.* (2000) explained that yield compensation due to variation in yield components is common in grain legumes.

Physiological mechanisms of yield variation

As noted, yield variation is a result of crop growth, DM accumulation, and remobilized assimilates from vegetative organs. The source of these assimilates is photosynthesis, which strongly depends on leaf growth (Monteith, 1977). The following sections focus on crop response to water deficit, and excess, in terms of leaf growth, radiation interception and photosynthesis.

Leaf growth

Leaf area is a key determinant of the amount of light intercepted which contributes directly to crop growth, TDM and grain yield. Leaf growth and development are subject to control by temperature and water supply (Monteith, 1977). Leaf growth is highly

responsive to water stress (Hsiao, 1993). A reduction in leaf expansion and canopy development caused by water lowers interception of radiation and photosynthesis, which leads to low DM accumulation and growth rate (Hsiao, 1993).

Hsiao (1973) held that expansion and division of leaf cells are plant processes which are most sensitive to water stress. Cell size and cell number of pea leaves were significantly reduced after plants were subjected to water deficit. This led to a reduction in leaf area (Lecoeur *et al.*, 1995). Leaf expansion started to decrease when the fraction of transpirable soil water dropped to a threshold level (Lecoeur and Sinclair, 1996). Lecoeur and Sinclair (1996) indicated that when the fraction of transpirable soil water decreased to 0.4, leaf area expansion of peas decreased linearly till it reached zero. Similar results were reported by Soltani *et al.* (2000) who showed that leaf expansion of chickpea started to decrease when the fraction of transpirable soil water reached 0.48. The rate of leaf production also declined when the fraction was less than 0.2 (Lecoeur and Guilioni, 1998).

In legumes the highest maximum LAI is observed in plants grown with sufficient soil moisture (Herbert, 1977). With full irrigation *Kabuli* chickpea can attain a maximum LAI (7.5) at about 100 d after emergence. In non-irrigated plots the highest LAI was 2.8, reached two weeks earlier than in fully irrigated plants (Anwar, 2001). Saxena *et al.* (1990) reported similar results with *Kabuli* chickpea. Other significant effects of irrigation on the LAI of grain legumes were reported; in mungbean (*Vigna radiata* L.) by Pannu and Singh (1993), pinto bean (*Phaseolus vulgaris* L.) cv. Othello by Dapaah *et al.* (2000), field bean by Husain *et al.* (1983) and in narrow-leafed lupin by Herbert (1977).

Leaf growth over time is green area duration (GAD) (Hunt, 1978). Total DM and seed yield are often significantly related to GAD (Ayaz, 2001). Variation in GAD explained 69 % of the variation in seed yield in *Kabuli* chickpea (Ayaz, 2001), which is similar to reported values in narrow-leafed lupin (Herbert, 1977). In faba bean (*Vicia faba* L.) variation in GAD accounted for 97 % of the variation in seed yield (De Costa *et al.*, 1997). These results suggest that irrigation increases LAI and GAD which effects photosynthesis and increases accumulated TDM and seed yield. However, if the LAI is greater than the critical LAI (that LAI at which 95 % of incident light is intercepted), GAD increases with no concomitant increase in TDM (Hay and Porter, 2006).

Radiation interception and photosynthesis

Monteith (1977) held that crop growth and productivity are mainly determined by the amount of radiation intercepted, the efficiency with which that it is used for TDM production and the efficiency with which TDM is partitioned into seed yield. As discussed above, water stress decreases LAI and GAD, which in turn reduces radiation interception. Zain *et al.* (1983) found, with conventional and semi-leafless peas, radiation absorbed was reduced from 410 MJ m⁻² with full irrigation to 300 MJ m⁻² under non-irrigated conditions. Increased radiation interception by irrigated *Kabuli* chickpea was reported by Saxena *et al.* (1990), Anwar (2001) and (Anwar *et al.*, 2003c).

A positive relationship between the amount of radiation intercepted, TDM and seed yield is widely accepted in grain legumes. In *Kabuli* chickpea, total intercepted radiation explained 80 % and 79 % of the variation in TDM production and seed yield (Ayaz, 2001). This result is in agreement with those for lentil (*Lens culinaris* Medik.) (McKenzie and Hill, 1991), pinto bean (Dapaah *et al.*, 2000) and field bean (Husain, 1984).

When the canopy is closed, water stress has less effect on leaf expansion but still reduces plant growth since opening of stomata and the photosynthetic apparatus are depressed (Hsiao, 1993; Turner *et al.*, 2005). Leport *et al.* (1999) showed that when a chickpea crop experienced water stress and leaf water potential fell to -3 MPa, photosynthesis was reduced by nearly 90 %. In other research, reduction in leaf water potential caused by terminal drought decreased the net photosynthesis rate from 21 to below 10 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Davies *et al.*, 1999). In white lupin, chickpea, field bean and lentil, photosynthesis and stomatal conductance were decreased with water stress (Leport *et al.*, 1998). A similar response was observed under water logged conditions. Leaf conductance in yellow and narrow-leafed lupin was reduced by 80 % after plants were water logged (Davies *et al.*, 2000b).

Grain legumes employ several mechanisms to adapt to water logging. Stomatal closure has been observed when legumes are water logged (Pezeshki, 1994). Stomatal closure might be triggered by increased levels of abscisic acid (ABA). Jackson and Hall (1987) reported that there was an increase in ABA content in peas when water logged. The extent of stomatal closure was less in an ABA mutant cultivar. Following stomatal closure there is a reduction in gas exchange and photosynthesis in narrow-leafed lupin (Davies *et al.*, 2000b). Similar results in snap bean (*Phaseolus vulgaris* L.) were reported by Singh *et al.* (1991) ; one day of flooding reduced net photosynthesis by 17 %. As flooding depletes

a large amount of O₂, nutrient uptake is inhibited. Other root functions are also influenced (Pezeshki, 1994). Root dry weight was reduced by 60 % in narrow-leafed lupin (Davies *et al.*, 2000a). The dry weight and volume of soybean roots was also reduced after flooding (Henshaw *et al.*, 2007). This can be caused by root cell death (Pezeshki, 1994).

Nitrogen accumulation as influenced by water deficit and excess

Nitrogen accumulation and partitioning

There are significant differences in N accumulation among legume species. Ayaz (2001) reported N accumulation ranged from 9.5, 12.9, 13.1, to 20 g m⁻² for lentil, chickpea, pea and narrow-leafed lupin. Research elsewhere has indicated N accumulation of lupin species varied from 48 (*Lupinus angustifolius* L.) to 472 (*L. albus* L.) kg N ha⁻¹ (Howieson *et al.*, 1998). There are two main sources of N for legume growth. While seedling growth depends on soil N, symbiotically fixed N can meet the crop demand at later growth stages (Ahlawat *et al.*, 2007). Kurdali (1996) reported that of 1,031 kg N ha⁻¹ accumulated in chickpea by physiological maturity, 60 % was from N fixation, 35 % from the soil and only 5 % from fertilizer. Howieson *et al.* (1998) also showed that the contribution of N fixed to total accumulated N varied from 20 to 97 % in narrow-leafed lupins.

Water deficit and water logging both strongly inhibit N accumulation in grain legumes (Bacanamwo and Purcell, 1999; Sinclair *et al.*, 2007). Davies *et al.* (2000b) reported that in yellow and narrow-leafed lupin there was no N accumulated during water logging. In soybean, N accumulation fell 59 % with flooding (Bacanamwo and Purcell, 1999). Serraj *et al.* (1997) indicated N accumulation, in non-irrigated soybean, decreased substantially, and was only 42 % of that in well watered soybean plants. Nitrogen accumulation in chickpea seed fell from 428 to 236 mg plant⁻¹ under water stress. As the majority of N accumulation is from N fixation, variation in total N accumulation might be attributable to that in N fixation.

Sinclair and de Wit (1975, 1976) hypothesized that most grain legumes are “self destructive crops”. During seed filling, legume crops require so much N for seed development that soil N uptake can not meet demand and N may be extracted from vegetative parts such as leaves or stems. As a result of N losses from vegetative parts, other physiological activities cease and vegetative parts senesce.

There are significant differences in N partitioning among cultivars. Umaid *et al.* (1982) reported that while total N in leaves of chickpea cv. Annigeri declined after flowering, in cultivar T-1-A the leaf N content increased after flowering. A report by Zeiher *et al.* (1982) indicated there were large differences in N redistribution from vegetative parts to seed in soybean. The amount of redistributed N varied from 30 to 100 %. The amount of remobilized N from shoots to pods was 81 % of total pod N.

The different proportions of N in various plant parts suggest that the NHI and N in plant residues can contribute to soil fertility (Howieson *et al.*, 1998). Ayaz (2001) reported a significant difference in N distribution in plant parts and NHI in four grain legumes. Among them, narrow-leafed lupin had the highest NHI (0.84). In *Kabuli* chickpea NHI was 0.75.

Nitrogen distribution is affected by water deficit and water excess conditions. In water logged condition, Davies *et al.* (2000b) found that narrow-leafed lupin and yellow lupin tended to distribute more N to roots. Foster *et al.* (1995) reported that in common beans (*Phaseolus vulgaris* L.) seed, when water supply was not a constraint, remobilization of N from leaves and stems contributed 27 % and 12 %, respectively to seed. Under a mild water deficit, the contribution increased to 55 % from leaves and 18 % from stems. A similar result was obtained by Davies *et al.* (2000e). Under water deficit the N contribution remobilized from the shoot increased to 91 % and 95 % for *Kabuli* and *desi* chickpea respectively. Variation in the amount N, distributed to seed, is believed to be influenced by sink strength. Davies *et al.* (2000e) reported a chickpea cultivar with high pod number had greater ability to extract more N into seed.

Nitrogen fixation

Fixed N represents a large proportion of total legume N content (Howieson *et al.*, 1998). The process is more sensitive to water deficit and excess than plant growth (Bacanamwo and Purcell, 1999; Sinclair *et al.*, 2007). During 7 days of flooding, there was no reduction in plant DM but N fixation was significantly reduced in soybean (Bacanamwo and Purcell, 1999). In narrow-leafed lupin, the maximum rate of N fixation was reduced by about 73 % after 14 weeks of water logging (Farrington *et al.*, 1977).

Nitrogen fixation is markedly decreased by water deficit (Sprent, 1971; Turner *et al.*, 2005). Streeter (2003) indicated that in soybean four weeks drought, during the reproductive stage, reduced fresh nodule weight by 38 % and acetylene reduction activity

by 50 %. Similar results were reported by Thomas *et al.* (2004) in mungbean and in common bean by Castellanos *et al.* (1996) and Ramos *et al.* (1999). Nitrogen fixation was reduced up to 80 % under severe drought. Kurdali *et al.* (2002) found that in chickpea, when irrigation kept the soil moisture content at 75 % of field capacity the amount of N fixed was 45 mg N plant⁻¹. With reduced irrigation keeping the soil moisture content at only 45 % of field capacity N fixation was less than 20 mg N plant⁻¹. Sprent (1973) indicated that in *Lupinus arboreus* Sims., acetylene reduction activity decreased significantly to near zero 10 d after withholding water. Zablutowicz *et al.* (1981) reported that in cowpea (*Vigna unguiculata* L. Walp.) N fixation fell from 137 to 60 $\mu\text{moles g}^{-1}$ nodule⁻¹ hour⁻¹ under well watered and drought conditions, respectively.

Physiological mechanisms of variation in N accumulation

Hardy and Havelka (1976) and Pate (1976) held that reduced N fixation under a water deficit was caused by reduced assimilate supply as a result of low photosynthesis not by nitrogenase concentration. Research has shown that a shortage of assimilate might not be the main factor but an inability of nodules to metabolize caused by down regulation of key enzymes may be more important (Schulze, 2004). The activity of sucrose synthase, an important enzyme with a key role in providing C substrate for N fixation and ensuring nodule function is a good example (Gordon *et al.*, 1999). Gordon *et al.* (1997) stated that a reduction in N fixation under water deficit might not be caused by a shortage of photosynthate but by an inability of sucrose synthesis in nodules. This was based on evidence that in soybean exposed to water stress, there was no significant difference in the sucrose content of well watered and water stressed plants but sucrose synthase activity, an important sucrose hydrolytic enzyme, was markedly reduced (Gordon *et al.*, 1997). This result is consistent with those of Ramos *et al.* (1999) who found reduced sucrose metabolism as sucrose content increased in nodules of common bean subjected to a 6 d water deficit. Streeter (2003) also showed that the decline in N fixation was not limited by C shortage for bacterioids as, in his experiment, there was an increase in polysaccharide.

Another mechanism responsible for reduction in N fixation is feedback inhibition (Serraj *et al.*, 2001). Sinclair and Serraj (1995) stated that ureide might be a key compound involved in feedback down regulation of N fixation. This is consistent with the results of Serraj *et al.* (1999) who compared the sensitivity of N fixation in different legume species to water deficit. Soybean cv. Biloxi was more sensitive to water deficit than white lupin cv.

Ultra as the former accumulated more ureide than the latter. Streeter (2003) argued that under water deficit high ureide accumulation could be attributed to lower demand for fixed N to support growth, thereby suppressing N fixation. This is consistent with the results of Hartwig and Trommler (2001) who indicated that because of a lack of growing tissue, after defoliation, there was a substantial increase in amino acids and a decrease in nitrogenase activity.

Wery (2005) speculated that if N fixation is not suppressed by C shortage support to bacteroids, N fixation might be reduced by low N demand for growth under conditions of water deficit. Begg and Turner (1976) reported that under water stress, cell division continued but at a slow rate. Hence, if the Streeter's (2003) and Wery's (2005) hypothesis is correct a slow rate of cell division would result in low N demand for cell growth, which in turn would cause a high plant N content and the down regulation of N fixation. Wery (2005) also observed that development of the final size of the apical bud in chickpea was reduced and this suggested low N demand.

Under water logging, the reduction in N accumulation can be explained in several ways. Denitrification tends to occur as anaerobic microorganisms use NO_3^- as an electron acceptor for respiration. In this process NO_3^- is converted to NO_2^- . Hence availability of the N ions which can be absorbed by plant roots might be reduced (Pezeshki, 1994). Root growth is also influenced by flooding (Henshaw *et al.*, 2007) and uptake of nutrient ions was decreased with a decline in ability to take them up caused by oxygen deficiency (Pezeshki, 1994). Nitrogen fixation was decreased by water logging and the effect might be attributed to a reduction in oxygen, nodule dry weight, bacteroid disintegration and a deterioration of vascular transfer cells involving transport of N from nodules (Minchin and Pate, 1975).

Response of yield to nitrogen fertilizer addition

High soil nitrate content adversely affects legume N fixation (Zhang and Smith, 2002). It decreases signal sending for symbiosis, deforming root hairs, rhizobial binding to the root and the number of infection threads. Nevertheless, there might be several rational reasons for applying N fertilizer to legumes. Grain legumes require large amount of N for seed development and N needs to be extracted from vegetative parts (Sinclair and de Wit, 1976). As N fixation can only partially meet the demand of seed growth, there might be a need for N from other source, i.e. fertilizer application (Gan *et al.*, 2003; Gutiérrez-Boem

et al., 2004). Before nodulation is fully established, legumes might experience N deficiency. Legume growth and seed yield responses might occur if N fertilizer is applied at a low rate (Sprent and Minchin, 1983).

There have been no consistent responses of soybean seed yield to N fertilizer (Salvagiotti *et al.*, 2008). While Gan *et al.* (2003) reported a positive response to N fertilizer application, Gutiérrez-Boem *et al.* (2004) reported that the application of N fertilizer, up to 100 kg N ha⁻¹, had no effect on soybean seed yield. No response to N fertilizer was also reported by (Hungria *et al.*, 2006). In Western Australia, application of N to narrow-leafed lupin crops is not a common practice (Longnecker *et al.*, 1998). Nitrogen fertilizer replaced N fixation and did not have any effect on total accumulated N in lupin. This suggests that N fertilizer application can substitute for N fixation (Evans *et al.*, 1987).

In chickpea, reported yield responses to N fertilizer are variable. In Canterbury, Kosgey (1994) reported that additional N fertilizer had no effect on seed yield but Verghis (1996) indicated that seed yield was increased by 18 % with an N fertilizer application of 90 kg N ha⁻¹ in a soil with a low available N. McKenzie and Hill (1995) observed that seed yield was increased by 17 % and 43 % with N fertilizer at 50 and 100 kg N ha⁻¹, in both *desi* and *Kabuli* chickpea. Walley *et al.*, (2005) reported no response to N application in *desi* or *Kabuli* chickpea. Kantar *et al.* (2003) reported no significant difference in seed yield and total N content in chickpea between plots receiving N fertilizer and no fertilizer if the crop was properly inoculated. Recently Palta *et al.* (2005) indicated that foliage N fertilizer application increased chickpea seed yield under terminal drought.

There are several explanations for the lack of response of chickpea to N fertilizer. McConnell *et al.* (2002) observed that N fertilizer increased biomass and total N content at anthesis but seed yield was not increased. They suggested that the lack of variation in seed yield and total N content might be ascribed to a low sink capacity of chickpea to remobilized N from vegetative to reproductive parts. An alternative explanation is that because additional N improved vegetative growth there might be competition for assimilates between new vegetative growth and seed (Bonfil and Pinthus, 1995); this explanation was based on a low partitioning degree to seed (Bonfil and Pinthus, 1995). Walley *et al.* (2005) observed that additional N did not change the total N content and they explained that N fertilizer might replace fixed N rather than supplementing and thus no gain in N was recorded.

Conclusions

1. *Kabuli* chickpea and narrow-leafed lupin are potential crops for Canterbury. Yield potentials are relatively high compared to world average yields.
2. Total DM accumulation and seed yield are strongly affected by conditions of water deficit and water excess. Yield and growth variation have been related to physiological responses.
3. Nitrogen accumulation and fixation are strongly affected by water supply. Understanding this can contribute greatly to improved N accumulation which in turn can result in yield increases, seed N content and a role of grain legumes in sustaining N availability.
4. Yield responses to N fertilize application are variable.

While there is a large body of evidence of positive responses in seed yields to irrigation in grain legumes, information on effect of water excess on growth and seed yields of grain legumes is very limited in Canterbury. There has also been no research on effect of both water deficit and excess on growth and seed yields and N accumulation in grain legumes. Response in seed yields of grain legumes to N fertilizer remains a question to be answered. Therefore, this field research was conducted to determine the effect of water deficit and excess on growth, seed yields and N accumulation in *Kabuli* chickpea and narrow-leafed lupin.

Chapter 3

Materials and Methods

Site

The experiment was conducted at the Horticultural Research Area, Lincoln University, Canterbury (Latitude 43° 38' S, Longitude 172° 30' E) between November 2007 and April 2008. Prior to the experiment the field was cropped in perennial ryegrass (*Lolium perenne* L. cv. Moata). The soil is a Templeton silt loam (New Zealand Department of Scientific and Industrial Research, 1968) which is further classified as an immature pallic soil (Hewitt, 1998) with water holding capacity, at field capacity, of 32 mm per 10 cm soil depth. Water deficits generally occur in this soil during the summer (Hewitt, 1998). A Ministry of Agriculture and Fisheries soil quick test taken prior to the experiment shows similar soil chemical properties to those of an immature pallic soil (Hewitt, 1998) (Table 3.1). The soil has a low sulphate status but is high in inorganic phosphorus readily available to plants and has high base saturation which determines a moderate degree of nutrient release to plants (McLaren and Cameron, 1996; Hazelton and Murphy, 2007).

Table 3.1. Soil chemical properties for 0-15 cm soil depth for the Horticultural Research Area, Lincoln University, Canterbury during 2007/08. Olsen-soluble P, Ca, Mg, K, Sulphate S and Na are measured as $\mu\text{g g}^{-1}$ soil, anaerobic mineralizable N as kg ha^{-1} and base saturation as a percentage.

pH	P	Ca	Mg	K	S	Na	N	Base saturation
6.1	26	1060	74	109	3	25	36	53.3

Experimental design

The experiment was a split-plot design with three replicates. To facilitate irrigation and minimize lateral movement of irrigated water, five irrigation levels (Table 3.2) were assigned as main plots and two legume species, *Kabuli* chickpea (*Cicer arietinum* L) (cultivar Principe) and narrow-leaved lupin (*Lupinus angustifolius* L) (cultivar Fest) were assigned as sub-plots. No space was left between sub-plots in each main plot but 3 m and 5 m spaces were left between main plots and replicates, respectively. Sub-plot size was

29.4 m², 14 m x 2.1 m (14 rows). Rows were 15 cm apart. The experiment, with a total of 30 plots, occupied 2,838 m².

Table 3.2. Irrigation treatments assigned in the experiment 2007/08.

Irrigation treatment	Amount of irrigation (mm)	
	<i>Kabuli</i> Chickpea	Narrow-leafed lupin
Nil	0	0
Half	165	165
Full	331	394
Double full	661	787
Full + N (Control)	331	394

Irrigation method

A T-tape irrigation system was used to ensure even distribution of irrigation water over the whole plot. Tapes were placed in every second crop row. The amount of water applied was measured by a flow meter (Neptune, type Sz, size 25.4 mm). Irrigation was applied when the volumetric soil moisture content was around 20 %. The amount of irrigation water applied (I) for full irrigation was equal to the actual soil moisture deficit, the difference between the actual soil moisture content (SMC_A) of the current week and field capacity (SMC_{FC}). Field capacity was estimated by wetting a small area in the experiment and draining the area drained for 48 hours. The volumetric soil moisture content was estimated to be 32 %.

$$I = SMC_A - SMC_{FC} \quad \text{Equation 3.1}$$

The volumetric soil moisture content was measured using the Time Domain Reflectometry (TDR) Trase system 1 Model 6050X1 from 0-30 cm soil depth. This volumetric moisture content was converted into depth of water per unit depth of soil per unit area i.e. millimetre of water per centimetre of soil and eventually into litres of water. A flow meter was used to ensure accurate application of irrigation water.

Crop husbandry

Standard farm practices were used for seedbed preparation. Seeds were cleaned and treated with the fungicide WAKIL[®] XL (metalaxyl-M a.i. 175 g kg⁻¹, fludioxonil a.i. 50 g kg⁻¹, cymoxanil a.i. 100 g kg⁻¹) at 2000 g (dissolved in water) 1000 kg seed. Inoculation

was also applied to seed before sowing. Seeds with germination rate higher than 85 % were sown with a cone seeder to attain target plant populations of 50 plant m⁻² and 100 plants m⁻² for *Kabuli* chickpea and narrow-leafed lupin, respectively. Weed control was achieved by the use of different herbicides at various stages. Treflan (trifluralin, a.i. 400 g l⁻¹) was applied at a rate of 1-2 l ha⁻¹ pre-sowing. Simazine 500 (simazine a.i. 500 g l⁻¹) was applied at 1.5 l ha⁻¹ at pre-emergence. The nitrogen fertilizer, calcium ammonium nitrate (27 % N) was applied after sowing at 150 kg N ha⁻¹ only to the control treatment of full irrigation with nitrogen.

Measurements and calculations

Growth and development

Dry matter (DM) accumulation was determined by the weekly increase in crop total DM. Samples were collected at random using two 0.1 m² quadrats. Samples were then dried to a constant weight. Sigmodial growth curves were fitted as general logistic function described by Gallagher and Robson (1984) using the maximum likelihood programme (Ross *et al.*, 1987).

$$Y = C/(1 + T \exp(-b(x-m)))^{1/T} \quad \text{Equation 3.2}$$

Where C is the expected maximum crop DM and T, b and m are constants. These values were used to calculate the weighted mean absolute growth rate (WMAGR), duration of exponential growth (DUR) and the maximum growth rate (MGR).

$$\text{WMAGR} = bC/2(T+2) \quad \text{Equation 3.3}$$

$$\text{DUR} = 2(T+2)/b \quad \text{Equation 3.4}$$

$$\text{MGR} = bC/(T+1)^{(T+1)/T} \quad \text{Equation 3.5}$$

Three crop phenological developmental stages, first flowering, first pod set and physiological maturity were recorded by general observation. The date of first flowering was recorded when 50 % of plants in a plot had one flower. The date of first pod set was recorded when 50 % of plants in a plot had set one pod. Physiological maturity was when

50 % of plants in a plot had one brown pod. Plots were harvested when plants had completely senesced.

Yield and yield components

At harvest maturity, total DM production, seed yield and harvest index (HI) were determined from an area of 1 m² taken from the 5 central rows of each plot using two cuts of 0.5 m². Samples were air dried to a level suitable for machine threshing. The total biomass of each air dried sample was recorded and the sample was then threshed in a stationary thresher. Straw and seed were separated. The weight of clean seed was recorded. Sub-samples of 200 g of chaff and straw from each plot were taken and dried to constant weight. The constant sub-sample dry weights were used to convert the total biomass of each sample to total DM production.

Yield components, i.e. the number of pods plant⁻¹, seeds pod⁻¹ and the hundred seed weight were measured from 5 randomly selected plants from the sampled areas for the final harvest. The hundred seed weight was determined from five sub-samples of the seed lot. The number of seeds m⁻² was determined from seed yield and seed weight. The HI was determined as the ratio between seed yield and total DM at final harvest.

Canopy development and radiation interception

Leaf area index (LAI) and the fraction of radiation transmitted (T_i) through the canopy were measured by a LICOR LAI 2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, Nebraska, USA). Leaf area duration was calculated following Hunt (1978). Measurements were taken at 7-10 day intervals from 28 d after sowing until the onset of complete plant senescence. In a plot, at each session, 2 above canopy and 6 below canopy measurements were taken. The fraction of radiation intercepted (F_i) was determined using the techniques of Gallagher and Biscoe (1978)

$$F_i = (1 - T_i)$$

Equation 3.6

Using a theoretical argument and measurements, Szeicz (1974) argued that the amount of incident photosynthetically active radiation (PAR) is constant at around 50 % of total solar radiation and suggested that PAR can be estimated from climatological measurement of solar radiation. In this study the amount of PAR absorbed (S_a) was

calculated from the product of the fraction intercepted and the amount of total incident PAR as described by Gallagher and Biscoe (1978).

$$S_a = F_i \times S_i \quad \text{Equation 3.7}$$

The fraction of radiation intercepted can be described by Beer's function (Equation 3.8) (Goudriaan and Monteith, 1990).

$$F_i = 1 - \exp(-KLAI) \quad \text{Equation 3.8}$$

The extinction coefficient (K) was estimated from the linear regression of LAI and the natural logarithm value of T_i (Equation 3.9).

$$K = -\ln(1-F_i)/LAI \quad \text{Equation 3.9}$$

In this study, radiation use efficiency (RUE) values were estimated using different methods, (1) as the ratio of above-ground DM at final harvest to total intercepted PAR, (2) as the slope of the linear relationship between accumulated above-ground DM and accumulated intercepted PAR using linear regression up to maximum DM as these methods are considered the more suitable measures (Sinclair and Muchow, 1999).

Nitrogen content

Plant samples were taken at three developmental stages, at first flowering, first pod set and at physiological maturity. Five plants were randomly selected and cut at ground level. The roots and nodules were removed with soil by digging up to 20 cm depth and 10 cm apart from the stems. The soil and roots with nodules were put together in a plastic bag and taken to the laboratory for wet-sieving to extract roots and nodules. Roots of the crops were easily differentiated from those of weed by their sizes and colours and appearance. Plant samples were separated as roots, nodules, stems, leaves, pod wall and seeds. Accumulated shed leaves were collected continuously up to physiological maturity.

Samples were dried at 65-70 °C and ground to a particle size of < 2 mm. The plant total N content was analysed using a modified Kjeldahl method (Blakemore *et al.*, 1987). This method uses acid digestion to convert plant N to ammonium sulphate. To ensure reduction of nitrate to ammonium, salicylic acid and sodium metabisulphite were used to

perform a series of conversion, Nitrate + salicylic acid → nitrosalicylic acid + sodium metabisulphite → aminosalicylic acid + sulphuric acid and catalyst (Potassium sulphate) → ammonium sulphate. Ammonium-nitrogen was determined using a Flow Injection Analyser. Working with different methods, Nelson and Sommers (1973) reported that this method had a higher N extraction efficiency from plant samples.

The method was applied in this work as follow: 0.1 g of well-ground plant sample was put into a digestion tube with the addition of 5 ml of digestion acid, a mixture of 3 % salicylic acid and concentrated H₂SO₄ (20 g of salicylic acid in 600 ml of concentrated H₂SO₄). After the plant sample was pre-digested by the mixed acid for 30 minutes, 0.25 g of sodium metabisulphate was added and the tube was then allowed to stand for 5 minutes. The digestion tube was then transferred to a heating block and heated for one hour with the temperature increased to 200 °C; by then SO₂ gas was produced. After frothing had subsided, 1 g of potassium sulphate (catalyst) was added. The accumulated solution in the digestion tube was heated for 3 to 4 hours and temperature increased to 380 °C. All N was converted to ammonium sulphate. The indicator of complete conversion was the colourlessness of the digest solution. The digestion tube was removed from the heating block. After allowing the digestion tube to cool down for 40 minutes, 50 ml of de-ionized water was added and the digestion tube was shaken on a vortex mixer to ensure that all added substances were dissolved. The mixture was then allowed to stand overnight for silica to settle. Samples were then filtered through Whatman No. 52 filter paper into a white polythene 100 ml bottle for N determination in a Flow Injection Analyser.

Nitrogen content in each plant part was estimated by the product of N concentration and DM of that plant parts. The total N per plant was computed by summation of N accumulated in each plant part. Nitrogen content in each plant part was converted to those per m² in the proportion of each plant part DM to the total above-ground DM per plant with a comparison to the total above-ground DM of samples per m², which were collected weekly for growth and yield analysis. The total N in crops per m² was also estimated in the same way.

Statistical analysis

To examine the response of growth, yield, and N accumulation in response to irrigation level and N fertilizer analysis of variance with designed contrasts was carried out as suggested by Little and Hills (1978). Standard errors of the mean (SEM), the coefficient

of variation (CV indicated as %), correlation coefficient, and percent variance accounted for (R^2) and coefficients of linear regression were also calculated. Regression coefficients were compared by T-test. Statistical analysis used the Genstat package (Version 10.1, Lawes Agricultural Trust, Rothamsted Experimental Station, Rothamsted).

Chapter 4

Growth, yield and yield components of *Kabuli* chickpea and narrow-leafed lupin as affected by different irrigation levels

Summary

Kabuli chickpea (*Cicer arietinum* L.) cv. Principe and narrow-leafed lupin (*Lupinus angustifolius* L.) cv. Fest were grown under different levels of irrigation, nil (water stressed), half irrigation, full irrigation, double irrigation (waterlogged) and full irrigation with 150 kg N ha⁻¹ (optimum, control plots) on a Templeton silt loam soil at Lincoln University, Canterbury, New Zealand in 2007/08 to examine growth, seed yield and yield component responses.

Averaged over the two legumes the weighed mean absolute growth rate (WMAGR) with full irrigation was 51 % higher than with no irrigation. Maximum dry matter (MaxDM) production and the maximum growth rate (MGR) followed the same trend. Although waterlogged conditions (double irrigation) did not significantly affect growth, the values for MaxDM, WMAGR, and MGR were lower than with full irrigation. Nitrogen fertilizer did not significantly improve growth of either legume. The irrigation by species interaction effect on growth was not significant. With full irrigation MGRs of *Kabuli* chickpea and narrow-leafed lupin were 27.6 and 34.1 g m⁻² day⁻¹, respectively.

Seed yields of *Kabuli* chickpea and narrow-leafed lupin with full irrigation were 326 and 581 g m⁻², respectively, a threefold increase over no irrigation. Averaged over the two legumes, the seed yield with double irrigation was reduced by 45 % compared with full irrigation. Nitrogen fertilizer did not significantly increase seed yield. The response in seed yield to irrigation was due to increased above-ground total dry matter (TDM) and growth since seed yields were closely related to TDM, WMAGR and MGR. The harvest index (HI) was increased by irrigation and was related to seed yield only in the narrow-leafed lupin. Seed yield was significantly related to pods plant⁻¹ (only in narrow-leafed lupin), seeds pod⁻¹ and seeds m⁻² (for both legumes). These yield components were also closely related to MaxDM, WMAGR and the MGR. Since seed yield and key yield components were significantly related to crop growth ($r \geq 0.54^*$) and were affected by irrigation level, crops should be irrigated over their whole growth cycle to ensure good

potential seed yields. These results suggest that N fertilizer application does not increase seed yield in these two legumes.

Introduction

In Canterbury, soil moisture deficit is a major constraint in annual crop production. To obtain their potential yield, crops need to be irrigated (McKenzie *et al.*, 1999). There is a concept of a “most sensitive period” to irrigation, particularly during flowering and that irrigation at this sensitive period would give higher yields (El Nadi, 1969, 1970; Malhotra *et al.*, 1997). However, Penman (1971), French and Legg (1979) and Day and Legg (1983) argued that there is no specifically responsive stage to irrigation and crop yield is decreased if the maximum soil moisture deficit exceed the critical limiting soil moisture deficit. The concept of a “critical limiting deficit” is substantially supported by later work (Husain *et al.*, 1983; Husain, 1984; Jamieson *et al.*, 1984; Anwar, 2001). There are several points which might be used to elaborate the two concepts. No response in seed yield to irrigation at other growth stages reported by El Nadi (1969) and Malhotra *et al.* (1997) might be attributed to the maximum soil moisture deficit not exceeding the critical limiting deficit which would decrease yield. Also, if the maximum soil moisture deficit was lower than the critical deficit, there might not be a yield response to irrigation. Working with chickpea, Anwar *et al.* (2003c) indicated that if the soil moisture deficit was less than 165 mm, there was no yield increase with additional irrigation. Also, there may be a concurrence between accumulated maximum soil moisture deficit reaching the critical limiting deficit and flowering (Wilson, 1987). The critical limiting deficit is important for conditions where a reduction in yield potential by an early water deficit can not be recovered by later irrigation (El Nadi, 1969) and a cost-benefit ratio can be analyzed using the critical limiting deficit concept (Jamieson *et al.*, 1984).

Water logging also constrains legume growth (Toker *et al.*, 2007). Seed yield of chickpea and narrow-leafed lupin was reduced up to 100 % (Toker *et al.*, 2007) and 61 % (Davies *et al.*, 2000c). The main causes of growth reduction under waterlogged conditions was oxygen deficiency which limited energy for plant nutrient uptake (Setter and Belford, 1990; McKenzie *et al.*, 1999). Nutrient availability was also affected by changes in the soil environment (Setter and Belford, 1990). For instance, denitrification reduced plant N availability (Pezeshki, 1994). There is less information on the effect of water logging on legume growth in Canterbury.

Sprent and Minchin (1983) suggested that starter nitrogen (N) fertilizer should be applied to legumes as they might experience N deficiency before they are well nodulated. Application of N fertilizer at later growth stages might also be important as during seed development legumes extract N from vegetative parts to deposit it in seed. This can lead to the cessation of carbon fixation by plant vegetative parts (Sinclair and de Wit, 1975, 1976). Nevertheless, there have been inconsistent responses to N application in soybean (*Glycine max* L.) (Salvagiotti *et al.*, 2008), *Kabuli* chickpea (Kosgey, 1994; Verghis, 1996), and narrow-leafed lupin (Seymour and Brennan, 1995; Ma *et al.*, 1998). These inconsistent results necessitate further research on the effect of N fertilizer on the TDM production and seed yield of *Kabuli* chickpea and narrow-leafed lupin.

A field experiment was conducted to test the effect of a range of water conditions from water deficit to excess and the effect of additional N fertilizer.

The specific objectives of this field study were:

1. To examine the yield response of *Kabuli* chickpea and narrow-leafed lupin to different levels of irrigation and additional N fertilizer.
2. To compare the yield response of the two grain legumes to irrigation treatments.
3. To examine the response of the HI and yield components to irrigation and to determine yield components which explained the variation in seed yield.

Results

Climate

Climate data were recorded at Broadfields Meteorological Station, Lincoln University, located about 1 km from the experimental site. Total solar radiation from October 2007 to April 2008 was 4 % higher than the long term average. During this period, solar radiation was higher than the long term, in all months with the exception of April. January received the highest solar radiation (725 MJ m⁻²) followed by December and November. Maximum and minimum temperatures were similar to the long term average (Figure 4.1). The warmest month was January when the maximum temperature reached 22 °C and the minimum temperature was 11 °C.

Rain from October 2007 to April 2008 was 3 % higher than the long term mean and a total of 363 mm fell. The higher rain, during this period, was due to more rain in October,

December and February. Rain in October and February was 47 %, 142 % higher than the long term average, respectively. In the other months, rainfall was lower than the long term average (Figure 4.1). Rainfall during crop growth from sowing to physiological maturity was 246 mm for narrow-leafed lupin and 220 mm for *Kabuli* chickpea.

Although rainfall was higher than the long term average, the Penman evapotranspiration was 4 % higher than the long term mean. This gave drier conditions and a higher water deficit than the long term average. January was driest month with the lowest rainfall (19 mm) over the period and the highest evapotranspiration (158 mm) (Figure 4.1). The dry January was associated with high temperatures and high amounts of incoming solar radiation.

Dry matter accumulation (Plant growth analysis)

Growth, i.e. dry matter (DM) accumulation, of the grain legumes was adequately described by a sigmoid growth pattern (Figure 4.2). Table 4.1 shows that maximum dry matter (MaxDM) was strongly affected by irrigation level, additional N fertilizer and legume species. On average, over the two legumes, the control plot (full irrigation with N fertilizer) gave the highest MaxDM (2,123 g m⁻²) but this was not significantly higher than with full irrigation alone (1,777 g m⁻²). The effect of additional N was obvious in *Kabuli* chickpea but not in narrow-leafed lupin. Additional N increased MaxDM in *Kabuli* chickpea by 50 % over full irrigation without extra N. Maximum DM was reduced in the nil irrigation treatment by 61 % compared to full irrigation. The weighted mean absolute growth rate (WMAGR) and the maximum growth rate (MGR) were significantly affected by the irrigation levels (Table 4.1). The duration of exponential growth ranged from 56 to 86 d. Full irrigation significantly increased both the WMAGR and MGR. The average values for the two species for WMAGR and MGR were 51 % and 48 % higher in fully irrigated plots than in non-irrigated plots.

Water logging (double the full irrigation treatment) did not significantly reduce the crop WMAGR or MGR compared to full irrigation (Table 4.1).

The weighted mean absolute growth rate and MGR of narrow-leafed lupin were not significantly higher than those of *Kabuli* chickpea. The maximum growth rate of *Kabuli* chickpea was 26.1 g m⁻² day⁻¹ and it was 29.7 g m⁻² day⁻¹ in narrow-leafed lupin (Table 4.1). There was no interaction between irrigation and species for these two growth parameters.

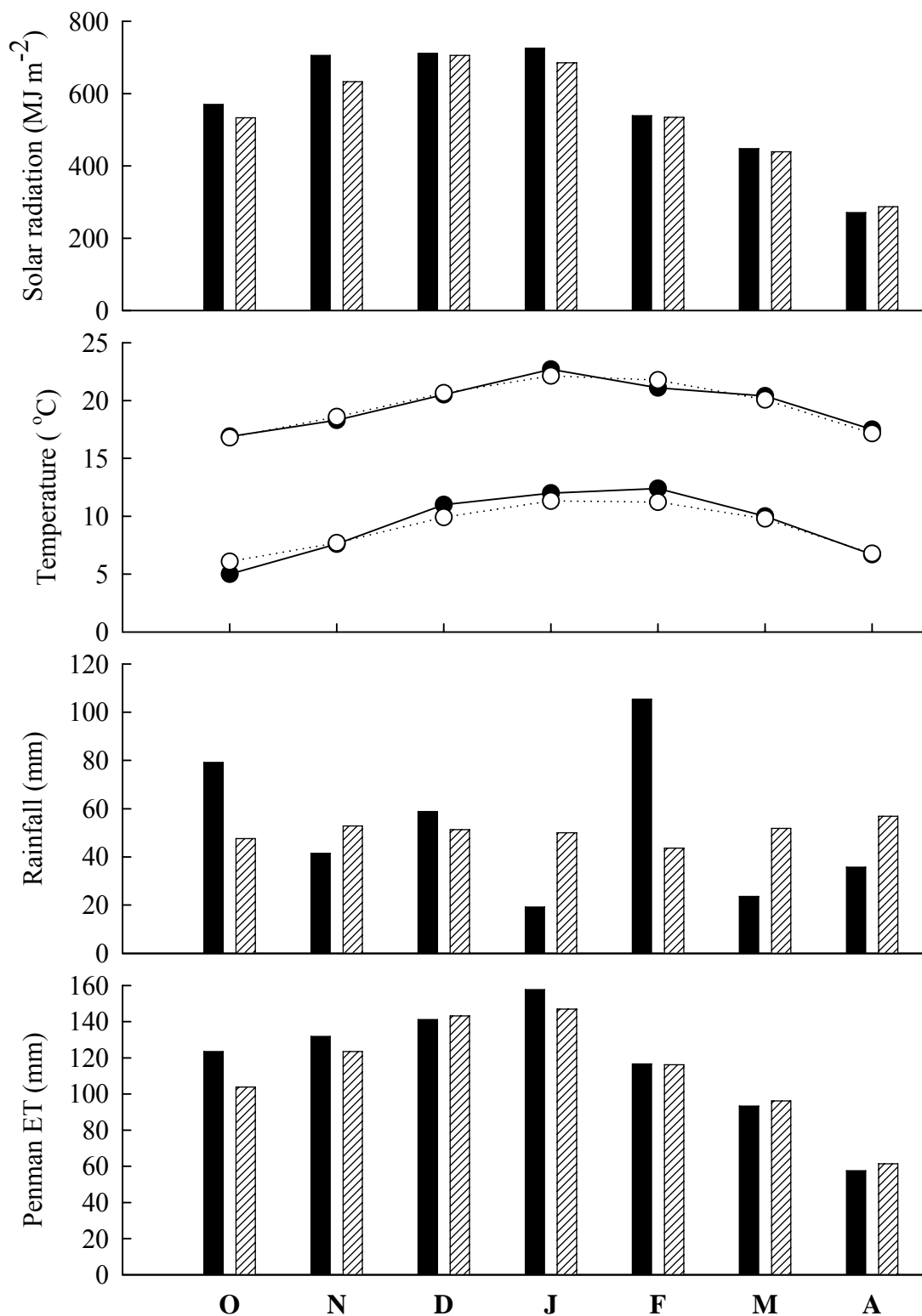


Figure 4.1. Weather data for 2007/08 (■,●) and long term means (▨,○) at Lincoln University, Canterbury, New Zealand. Long term values recorded from 1961 to 2008.

The designed contrast between full irrigation and full irrigation with N at 150 kg N ha⁻¹ showed there was no significant effect of N on the WMAGR or the crop MGR. The interaction N by species was not significant (Table 4.1).

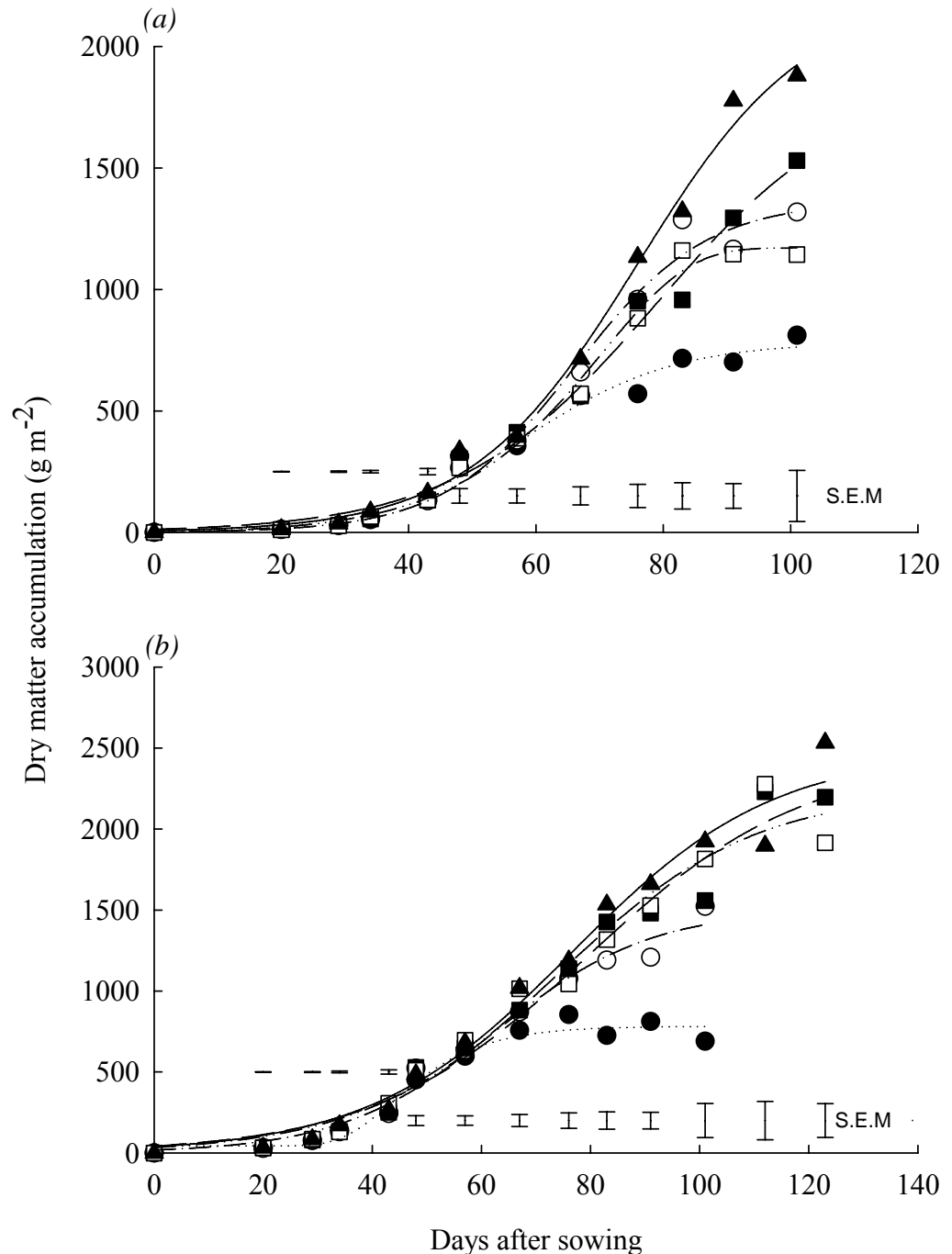


Figure 4.2. Accumulated dry matter of *Kabuli* chickpea (a) and narrow-leafed lupin (b) grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. $Y = C/(1 + T \exp(-b(x-m)))^{1/T}$. S.E.M = standard error of mean.

Table 4.1. The effect of irrigation level, N fertilizer application on maximum dry matter, (MaxDM), duration of exponential growth (DUR), weighted mean absolute growth rate (WMAGR) and maximum growth rate (MGR) of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	MaxDM (g m ⁻²)	DUR (days)	WMAGR (g m ⁻² day ⁻¹)	MGR (g m ⁻² day ⁻¹)
Nil	690	56	13.7	20.9
Half	1277	74	17.8	26.5
Full	1777	86	20.8	30.9
Double	1536	87	18.0	26.7
S.E.M	172.8	9.3	1.6	2.4
Significance	**	ns	*	*
Significant trends				
Linear (I _L)	ns	ns	ns	ns
Quadratic (I _Q)	*	ns	*	*
Species (S)				
<i>Kabuli</i> chickpea	1302	76	17.5	26.1
Narrow-leaved lupin	1660	83	19.9	29.7
S.E.M	74.9	5.8	0.8	1.3
Significance	**	ns	ns	ns
Nitrogen fertilizer				
<i>Kabuli</i> chickpea at Full + N	2105	96	22.7	33.5
Narrow-leaved lupin at Full + N	2140	92	23.9	35.5
Means of Full + N	2123	94	23.3	34.5
Designed contrast (Full + N vs. Full)	***	ns	ns	ns
CV %	19.6	28.2	17.4	18.2
Significant interactions				
I x S	*	ns	ns	ns
I _L x S	*	ns	ns	ns
I _Q x S	ns	ns	ns	ns
(Full + N vs. Full) x S	ns	ns	ns	ns

ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001.

Table 4.2. Irrigation by species interaction effect on maximum dry matter, (MaxDM) and duration of exponential growth (DUR) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	MaxDM (g m ⁻²)		DUR (days)	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	683	698	63	49
Half	1255	1298	71	77
Full	1403	2152	78	94
Double	1062	2009	71	102
Full + N	2105	2140	96	92
S.E.M	209.5		18.4	
CV	10.6		28.2	

Table 4.3. Irrigation by species interaction effect on weighted mean absolute growth rate (WMAGR) and maximum growth rate (MGR) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	WMAGR (g m ⁻² day ⁻¹)		MGR (g m ⁻² day ⁻¹)	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	12.31	15.17	18.51	23.27
Half	17.97	17.61	26.75	26.26
Full	18.56	22.96	27.61	34.14
Double	16.16	19.81	24.16	29.19
Full + N	22.67	23.9	33.49	35.47
S.E.M	2.04		3.17	
CV	17.4		18.2	

Total dry matter and seed yield

There was a significant response in TDM to irrigation level at the final harvest (Figure 4.3). Averaged over the two legume species, there was a threefold increase in TDM from nil to full irrigation but TDM declined by 30 % from full irrigation to double irrigation (Table 4.4).

The response of TDM at final harvest to irrigation was significantly different between the two legumes (Figure 4.3). Narrow-leafed lupin responded more to irrigation than *Kabuli* chickpea. While there was a fourfold increase in TDM in narrow-leafed lupin, and threefold increase was recorded in *Kabuli* chickpea. In waterlogged conditions (double

irrigation), TDM was decreased by 30 % from full irrigation in both *Kabuli* chickpea and narrow-leafed lupin. Under full irrigation, the total dry matter was 1205 and 2267 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin, respectively (Figure 4.3).

The addition of N fertilizer had no significant effect on TDM. There was also no interaction effect between N and legume species on TDM at final harvest. Averaged over legume species, TDM with full irrigation and N fertilizer applied was 1856 g m⁻² (Table 4.4).

Seed yield followed the same pattern as TDM (Figure 4.3). Averaged over the two legumes, full irrigation produced the highest seed yield, 454 g m⁻² (Table 4.4). Seed yield in full irrigation was three times as high as nil irrigation. Double irrigation (waterlogged condition) decreased yield by 45 % below the full irrigation yield (Figure 4.3).

Averaged across irrigation levels, narrow-leafed lupin produced a seed yield 34 % higher than *Kabuli* chickpea (Table 4.4). There was also an interaction between legume species and irrigation levels (Table 4.4). While the seed yields of the two legumes were not significantly different in both nil irrigation and half irrigation, seed yields were different in full and double irrigated plots. Under the latter conditions, narrow-leafed lupin out yielded *Kabuli* chickpea by 78 % and 108 %, respectively (Figure 4.3). While full irrigation increased seed yield of narrow-leafed lupin by six times, there was only a twofold increase in *Kabuli* chickpea seed yield. The trend was reversed with double irrigation. Seed yield of narrow-leafed lupin was decreased by 42 % but *Kabuli* chickpea by 51 %.

Seed yield was not affected by additional N fertilizer (Table 4.4). The interaction between N fertilizer and legumes species was significant. The seed yield of narrow-leafed lupin was higher than *Kabuli* chickpea in the two treatments. Averaged over the two legumes, seed yield of full irrigation with additional N fertilizer was 415 g m⁻².

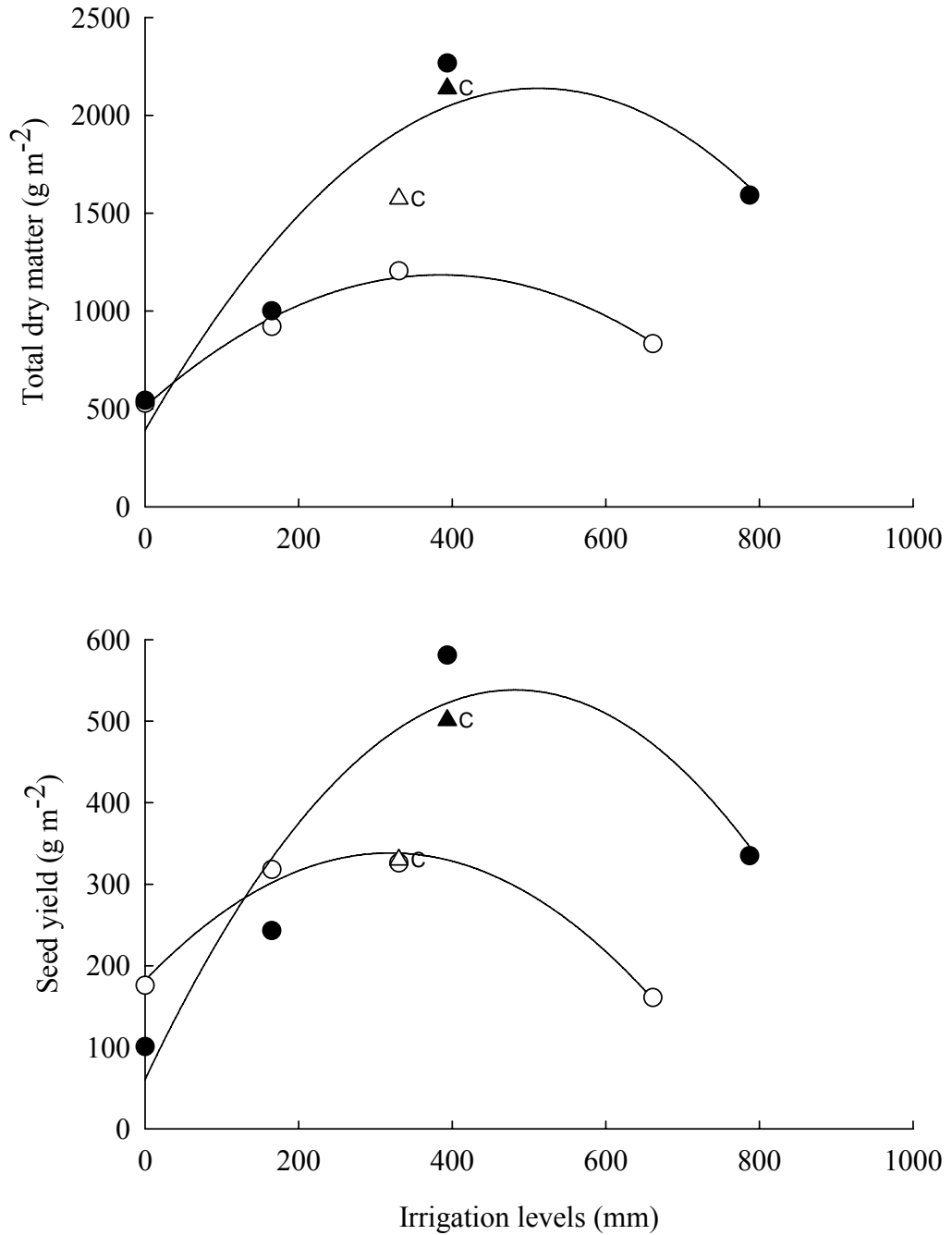


Figure 4.3. Total dry matter and seed yield responses of *Kabuli* chickpea and narrow-leaved lupin to different levels of irrigation. For *Kabuli* chickpea (○), relationships between irrigation levels and TDM and seed yield are $Y = -0.005X^2 + 3.50X + 511.28$ ($R^2 = 0.99$) and $Y = -1.53X^2 + 0.98X + 182.02$ ($R^2 = 0.98$). For narrow-leaved lupin (●), relationships between irrigation levels and TDM and seed yield are $Y = -0.01X^2 + 6.83X + 390.34$ ($R^2 = 0.89$) and $Y = -0.002X^2 + 1.98X + 60.30$ ($R^2 = 0.89$); respectively. Controls: full irrigation with 150 kg N ha⁻¹ for *Kabuli* chickpea (△C) and for narrow-leaved lupin (▲C).

Table 4.4. Effect of irrigation level and N fertilizer application on seed yield, TDM and crop harvest index of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Seed yield (g m ⁻²)	Total dry matter (g m ⁻²)	Crop harvest index
Nil	139	536	0.25
Half	280	961	0.30
Full	454	1736	0.27
Double	248	1212	0.20
S.E.M	32.4	133.6	0.02
Significance	***	***	ns
Significant trends			
Linear (I _L)	ns	**	*
Quadratic (I _Q)	***	**	ns
Species (S)			
<i>Kabuli</i> chickpea	262	1012	0.27
Narrow-leafed lupin	352	1508	0.22
S.E.M	23.3	75	0.01
Significance	*	***	**
Nitrogen fertilizer			
<i>Kabuli</i> chickpea at Full + N	330	1574	0.21
Narrow-leafed lupin at Full + N	501	2138	0.23
Means of Full + N	415	1856	0.22
Designed contrast (Full + N vs. Full)	ns	Ns	ns
CV %	29.4	23.1	14.9
Significant interactions			
I x S	*	*	**
I _L x S	*	*	*
I _Q x S	ns	ns	ns
(Full + N vs. Full) x S	ns	ns	ns

ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001.

Harvest index

The averaged values of HI over the two grain legumes were not significantly different among irrigation levels. However, there was a significant interaction effect between irrigation levels and species (Table 4.4). While HI of *Kabuli* chickpea tended to decline with irrigation, HI of narrow-leafed lupin increased with increased irrigation up to full irrigation. In *Kabuli* chickpea, the crop produced the highest HI (0.34) with half irrigation and the lowest with double irrigation (0.19). In contrast, narrow-leafed lupin had

the highest HI (0.26) under full irrigation and the lowest in no irrigation plots (0.17) (Figure 4.4). Averaged over irrigation levels, *Kabuli* chickpea had a significantly higher HI than narrow-leafed lupin (Table 4.4).

There was no effect of additional N fertilizer on HI. However, both legumes tended to produce lower HIs in plots with additional N than full irrigation (Figure 4.4). The reduction of HI by additional N fertilizer was more obvious in *Kabuli* chickpea than narrow-leafed lupin.

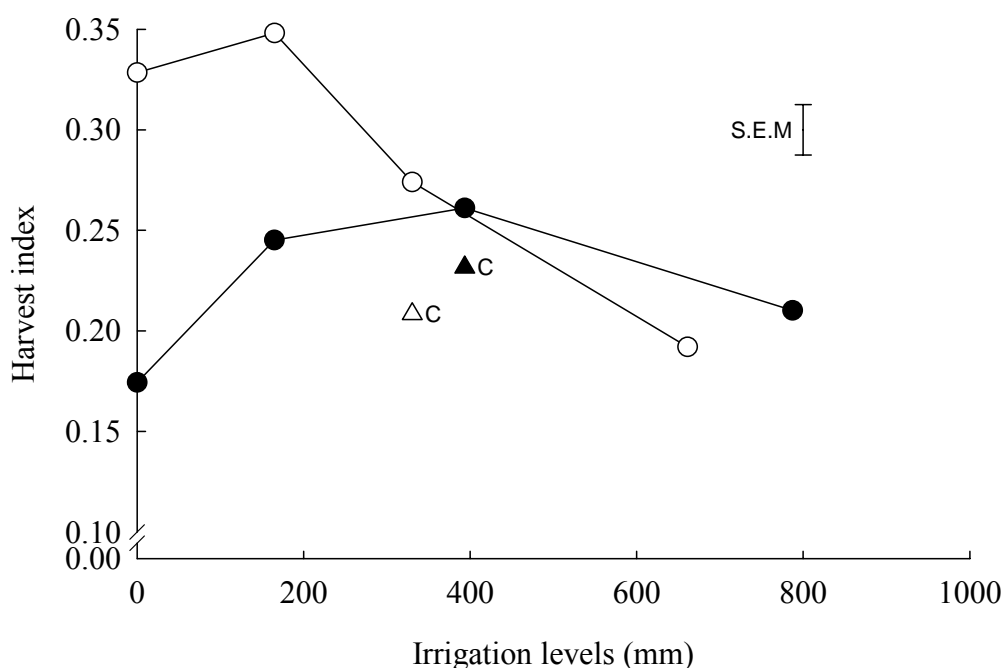


Figure 4.4. Crop harvest index response of *Kabuli* chickpea (○) and narrow-leafed lupin (●) to different levels of irrigation. Controls: full irrigation with 150 kg N ha⁻¹ for *Kabuli* chickpea (△C) and for narrow-leafed lupin (▲C). S.E.M = standard error of mean.

Yield components

Number of pods plant⁻¹

The effects of irrigation, additional N fertilizer and species on yield components are shown in Table 4.5. Increasing the amount of irrigation to the full requirement of the crop significantly enhanced the number of pods per plant threefold. While there was no interaction of irrigation and species, the number of pods differed significantly between the two species (Table 4.6). Averaged across the irrigation levels, *Kabuli* chickpea produced 27 pods per plant but narrow-leafed lupin plants had only 9 pods. There was a tendency

toward a reduction in number of pods plant⁻¹ with double irrigation but this was not different from fully irrigated plots. The number of pods was also not affected by additional N fertilizer application and the interaction between fertilizer and species was not significant.

Number of seeds pod⁻¹

Irrigation significantly affected the number of seeds pod⁻¹ (Table 4.5). Full irrigation produced the highest number of seeds and the lowest number was recorded in the unirrigated and double irrigated plots. On average, *Kabuli* chickpea produced one seed per pod whilst, narrow-leafed lupin had four seeds per pod (Table 4.5). There was an interaction between irrigation and species on the number of seeds per pod (Table 4.6). While *Kabuli* chickpea had the lowest seeds per pod with double irrigation, narrow-leafed lupin had the lowest in unirrigated plots. With double irrigation, *Kabuli* chickpea had an average seed number less than one. In contrast, in half and fully irrigated plots the number was higher than one. In narrow-leafed lupin, the number of seeds per pod increased from nil irrigation to full irrigation by 28 %. The number of seeds per pod was not affected by N fertilizer (Table 4.5).

100 seed weight

Kabuli chickpea seed (26 g per 100 seeds) was nearly twice as heavy as lupin seed (16 g per 100 seeds) (Table 4.5). Table 4.7 shows that while the hundred seed weight of narrow-leafed lupin was not significantly affected by irrigation level, the hundred seed weight of *Kabuli* chickpeas decreased by 30 % with full irrigation. Double irrigation and full with N fertilizer treatment did not significantly affect the one hundred seed weight of both *Kabuli* chickpea and narrow-leafed lupin.

Table 4.5. Effect of irrigation level and N fertilizer application on yield components of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Pods plant ⁻¹	Seeds pod ⁻¹	100 seed weight (g)	Seeds m ⁻²
Nil	6	2	23	611
Half	11	3	24	1262
Full	25	3	20	2464
Double	20	2	17	1489
S.E.M	2.57	0.09	1.92	196.1
Significance	**	*	ns	***
Significant trends				
Linear (I _L)	**	ns	*	**
Quadratic (I _Q)	*	**	ns	***
Species (S)				
<i>Kabuli</i> chickpea	27	1	26	1066
Narrow-leaved lupin	9	4	16	2173
S.E.M	2.43	0.05	0.73	119.1
Significance	***	***	***	***
Nitrogen fertilizer				
<i>Kabuli</i> chickpea at Full + N	40	1	22	1464
Narrow-leaved lupin at Full + N	13	4	16	3085
Means of Full + N	26	3	19	2274
Designed contrast (Full + N vs. Full)	ns	ns	ns	ns
CV %	52.9	8.1	13.6	28.5
Significant interactions				
I x S	ns	*	**	*
I _L x S	ns	*	***	ns
I _Q x S	ns	*	ns	*
(Full + N vs. Full) x S	ns	ns	ns	ns

ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001.

Table 4.6. Irrigation by species interaction effect on number of pods per plant and seeds per pod of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	Pods plant ⁻¹		Seeds pod ⁻¹	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	8.5	4.3	1.007	3.43
Half	16.8	5.7	1.082	4.01
Full	36.3	13.2	1.045	4.38
Double	31.3	8.7	0.985	4.01
Full + N	40.3	12.5	1.026	4.04
S.E.M	4.62		0.1195	
Significance	ns		*	
CV	52.9		8.1	

ns = non-significant, * = P < 0.05.

Table 4.7. Irrigation by species interaction effect on 100 seed weight (g) and number of seeds per metre squared of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	100 seed weight (g)		Seeds m ⁻²	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	32.6	13.86	532	690
Half	31.7	16.08	1012	1512
Full	22.83	16.72	1435	3492
Double	18.13	16.1	888	2089
Full + N	22.37	16.25	1464	3085
S.E.M	2.239		271.9	
Significance	**		*	
CV	13.6		28.5	

* = P < 0.05, ** = P < 0.01.

Number of seeds m⁻²

The number of seeds m⁻² increased with increase in irrigation level. Full irrigation produced the highest seed number per meter squared (Table 4.5). No irrigation and double irrigation decreased seeds m⁻² by 75 % and 40 %, respectively. The number of seeds m⁻² in narrow-leafed lupin was more than twice as high as *Kabuli* chickpea. Additional N fertilizer did not significantly change the number of seeds m⁻².

Correlations between yield and yield components

Table 4.8 shows relationships between yield and yield components varied between *Kabuli* chickpea and narrow-leafed lupin. In *Kabuli* chickpea, seed yield was positively related only to seeds pod⁻¹ and seeds m⁻² whilst in narrow-leafed lupin seed yield was positively related to pods plant⁻¹, seeds pod⁻¹ and seeds m⁻². In the two legumes, pods plant⁻¹ was related to seeds m⁻². In *Kabuli* chickpea, pods plant⁻¹ was negatively related to 100 seed weight; in contrast, the two traits were not related in narrow-leafed lupin.

In both *Kabuli* chickpea and narrow-leafed lupin, pods plant⁻¹ and seeds m⁻² were strongly related to seed yield. There were also higher significant relationship between crop growth parameters and the two traits (Table 4.9; Figure 4.5 and 4.6).

Table 4.8. Correlation matrices between seed yield and yield components of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

	Seed yield	Total dry matter	Harvest index	Pods plant ⁻¹	Seeds pod ⁻¹	100 seed weight
<i>Kabuli</i> chickpea						
Total dry matter	0.70**					
Harvest index	0.31ns	- 0.42 ns				
Pods plant ⁻¹	0.28ns	0.69**	- 0.62*			
Seeds pod ⁻¹	0.61*	0.13 ns	0.56*	0.07 ns		
100 seed weight	0.24ns	- 0.34 ns	0.86**	- 0.56*	0.42 ns	
Seeds m ⁻²	0.79**	0.92**	-0.26ns	0.65**	0.22ns	-0.37ns
Narrow-leafed lupin						
Total dry matter	0.98**					
Harvest index	0.56*	0.44 ns				
Pods plant ⁻¹	0.86**	0.90**	0.34 ns			
Seeds pod ⁻¹	0.66**	0.66**	0.50 ns	0.74**		
100 seed weight	0.51ns	0.45 ns	0.78**	0.44 ns	0.71**	
Seeds m ⁻²	0.99**	0.98**	0.53*	0.85**	0.62*	0.46ns

ns = non-significant, * = P < 0.05 and ** = P < 0.01.

Table 4.9. Correlation matrices between growth parameters and seed yield and yield components of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

	Seed yield	Harvest index	Pods plant ⁻¹	Seeds pod ⁻¹	100 seed weight	Seeds m ⁻²
<i>Kabuli</i> chickpea						
MaxDM	0.57*	-0.43ns	0.54*	0.04ns	-0.28ns	0.73**
DUR	0.13ns	-0.26ns	0.07ns	-0.013ns	-0.11ns	0.18ns
WMAGR	0.61*	-0.28ns	0.66**	0.09ns	-0.19ns	0.75**
MGR	0.60*	-0.28ns	0.66**	0.09ns	-0.19ns	0.73**
Narrow-leaved lupin						
MaxDM	0.82**	0.32ns	0.89**	0.75**	0.49ns	0.82**
DUR	0.59*	0.16ns	0.63**	0.49ns	0.22ns	0.60*
WMAGR	0.65*	0.52*	0.66**	0.69**	0.72**	0.62*
MGR	0.62*	0.51*	0.63*	0.67**	0.72**	0.59*

ns = non-significant, * = P < 0.05 and ** = P < 0.01.

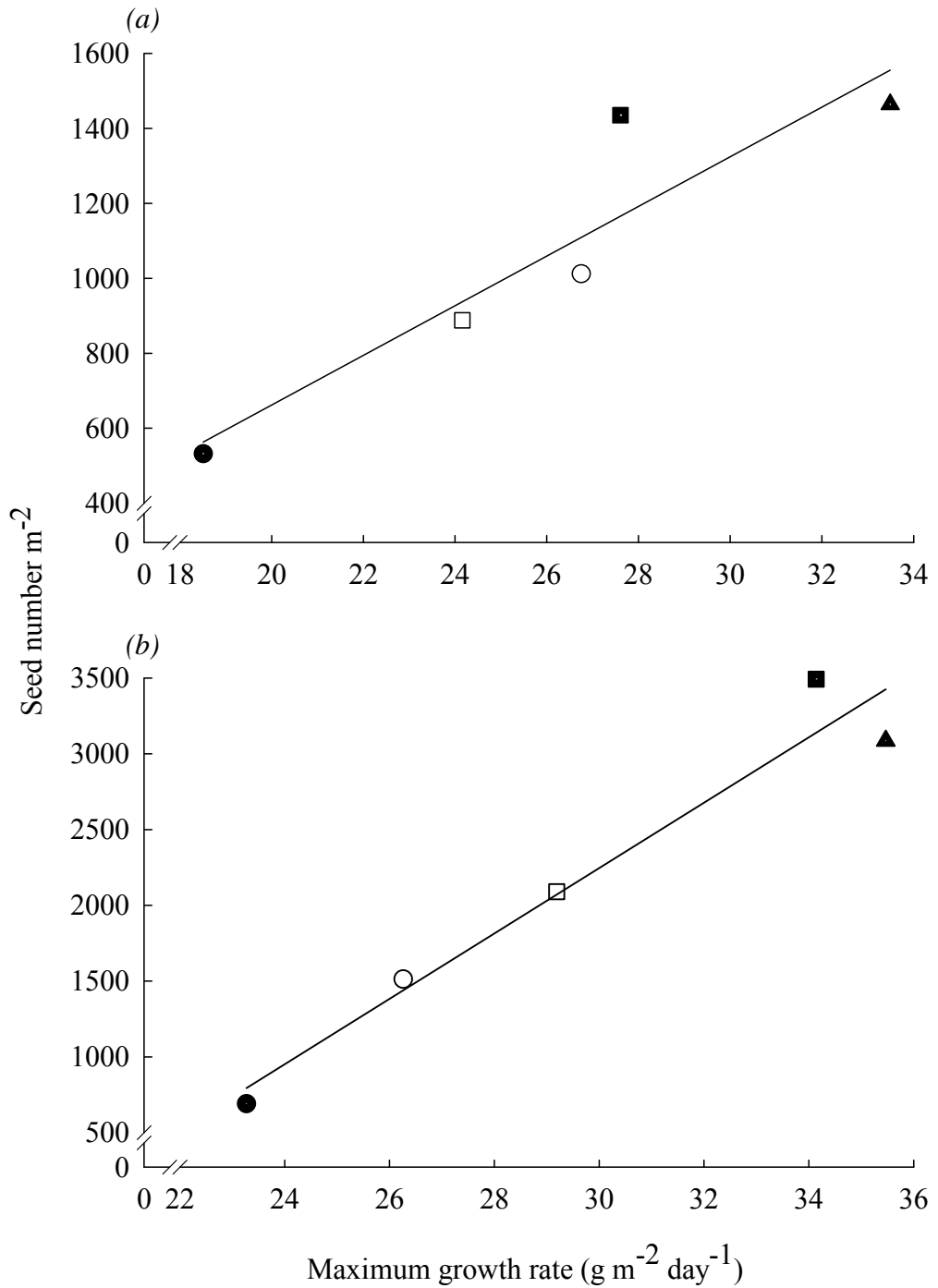


Figure 4.5. Relationship between maximum growth rate and seed number m⁻² of *Kabuli* chickpea (a) and narrow-leaved lupin (b) grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. The relationship equations are (a), $Y = -662.91 + 66.24X$ ($R^2 = 0.85$) and (b), $Y = -4228.73 + 215.81X$ ($R^2 = 0.95$).

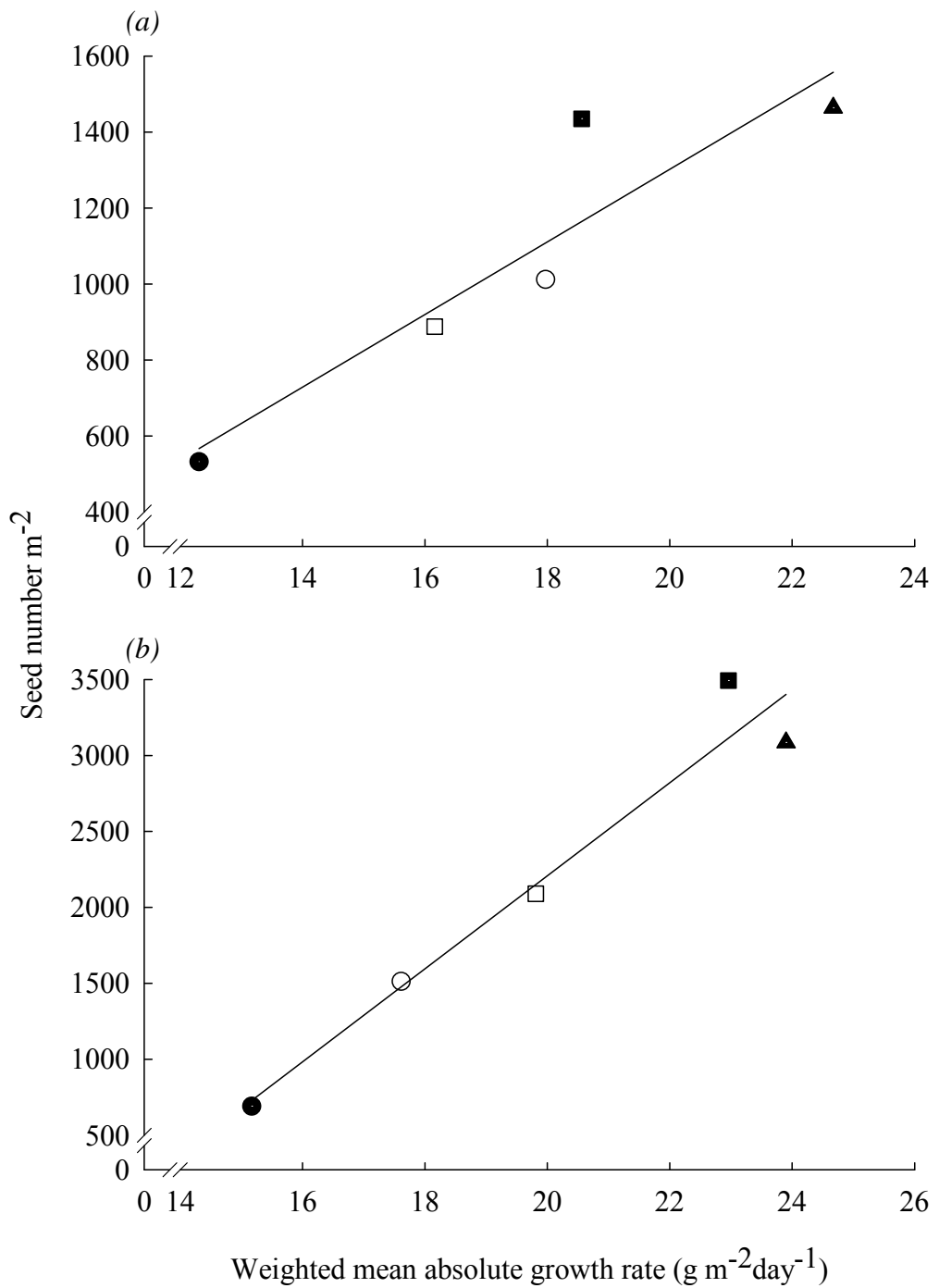


Figure 4.6. Relationship between weighted mean absolute growth rate and seed number m⁻² of *Kabuli* chickpea (a) and narrow-leaved lupin (b) grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. The relationship equations are (a), $Y = -611.08 + 95.66X$ ($R^2 = 0.85$) and (b), $Y = -3914.85 + 306.11X$ ($R^2 = 0.95$).

Discussion

Dry matter accumulation (Plant growth analysis)

The response of DM accumulation to irrigation (Figure 4.2) are similar to other results in *Kabuli* chickpea (Kosgey, 1994; Anwar *et al.*, 2003b), in pinto bean (Dapaah *et al.*, 2000), lentil (McKenzie, 1987) and field bean (Husain, 1984). Irrigation substantially increased MaxDM. Dapaah (1997) found that MaxDM of irrigated pinto bean was 36 % higher than non-irrigated crops. Working with *Kabuli* chickpea, Anwar *et al.* (2003b) reported that there was a 64 % increase of MaxDM in irrigated plots over unirrigated plots. In this study, full irrigation increased MaxDM by 105 %. The reason why the response to irrigation in this study is higher than the work of Anwar *et al.* (2003b) is due to the growing conditions. The 2007/08 growing condition was drier than that of Anwar *et al.* (2003b) as the total amount of full irrigation to replace the water deficit in this study (331 mm) was higher than that in Anwar *et al.* (2003b) (231 mm) and the crop growth durations are not so different. The unirrigated crop in this study experienced more severe water stress than Anwar *et al.* (2003b), which led to greater differences in MaxDM between fully irrigated and unirrigated crops.

The results reported here showed positive responses to irrigation in both WMAGR and MGR. In *Kabuli* chickpea, WMAGR in full irrigation was 18.56 g m⁻² day⁻¹ and in narrow-leafed lupin was 22.96 g m⁻² day⁻¹. This result is similar to that reported by Verghis (1996); the WMAGR was 21 g m⁻² day⁻¹ for fully irrigated chickpea. The maximum growth rates were 27.6 and 34.1 g m⁻² day⁻¹ for fully irrigated chickpea and narrow-leafed lupin, respectively. These values are similar to those for C3 crops reported by Monteith (1978) with a range from 34 to 39 g m⁻² day⁻¹. Fully irrigated crops produced 51 % and 45 % increases in WMAGR and MGR over non irrigated crops, respectively. Working with pinto bean, Dapaah *et al.* (2000) found that WMAGR and MGR in irrigated crops were nearly 100 % higher than without irrigation. It has been established that water stress can affect crop growth by reductions in leaf growth and stomatal opening. In this study, water stress reduced leaf area index, green leaf area duration and the amount of radiation intercepted as described in Chapter 5. Hence, the reduction in crop growth rates are attributed to reduced radiation intercepted. Ball *et al.* (2000a) also indicated that in soybean slow crop growth rates resulted from a low light interception which was a result of a lower leaf area index compared to a critical leaf area index.

Responses to water

Total dry matter

Above ground TDM at harvest maturity varied significantly among different irrigation levels (Table 4.4). Full irrigation produced three times more total dry matter than unirrigated plots and double irrigation decreased above ground TDM by 30 %. There have been many reports indicating positive response to irrigation of grain legumes; narrow-leaved lupin (Herbert, 1977), lentils (McKenzie, 1987), field bean (Husain, 1984) and *Kabuli* chickpea (Anwar, 2001). The growth responses to irrigation can be results of high soil moisture content which maintains high plant water status, leaf water potential, stomatal opening, stomatal conductance and photosynthesis. Leport *et al.* (1998; 1999) reported that as water stress occurred, leaf water potential of several legumes species including chickpea and lupin dropped and photosynthesis and stomatal conductance decreased notably. The positive response observed in this study means that the fully irrigated crops grew at their potential rates and their physiological processes were unaffected by water stress.

Water excess in double irrigation plots reduced TDM by 30 % for both *Kabuli* chickpea and narrow-leaved lupin in this study. Davies *et al.* (2000c) reported that DM of yellow lupin and narrow-leaved lupin were reduced by 19 % and 50 %, respectively after 14 days of waterlogging. Physiological responses of legumes to water logging can cause low dry matter production. The increase in ABA content in waterlogged crops can cause the stomata to close (Jackson and Hall, 1987) and can be responsible for reduction in leaf gas exchange and photosynthesis as those process were reduced in waterlogged conditions (Davies *et al.*, 2000b). Low oxygen in the rhizosphere results in limitation of plant growth in waterlogged soil. The process of energy production changes because of no oxygen. Alcoholic fermentation occurs to produce energy, but there is only a small amount, which restricts nutrient uptake causing low shoot growth (Setter and Belford, 1990).

Total dry matter production differed significantly between *Kabuli* chickpea and narrow-leaved lupin (Table 4.4). This result is consistent with that of Ayaz (2001). This difference can be attributed to growth duration of leaves as growth or the accumulation of DM is dependent on the total amount of radiation intercepted and the efficiency of conversion of those intercepted radiation into DM (Monteith, 1977). Total dry matter production was strongly related to leaf area duration in *Kabuli* chickpea (Anwar, 2001), narrow-leaved lupin and other legume species (Ayaz, 2001). Hence, as narrow-leaved lupin

had a longer leaf area duration than *Kabuli* chickpea (Ayaz, 2001) it intercepted more radiation and produced more TDM. The result reported here also confirms that narrow-leaved lupin had significantly longer leaf area duration and intercepted more PAR (photosynthetically active radiation) than *Kabuli* chickpea (Table 5.1).

Seed yield

The results of the present study indicated that there was a threefold increase in seed yields of *Kabuli* chickpea and narrow-leaved lupin by irrigation (Table 4.4). Palta and Plaut (1999) found a 44 % increase in seed yield of narrow-leaved lupin with full irrigation. Similarly, Husain *et al.* (1988a) indicated that seed yield of field bean was increased by 45 % with irrigation. Recent work on *Kabuli* chickpea by Anwar (2001) showed that irrigation increased seed yield by 74-124 %. The seed yield response to irrigation in the present experiment is much more higher than Anwar's (2001) result. This can be attributed to the drier conditions and lower rainfall. The Penman evapotranspiration during this study was 4 % higher the long term and the total rainfall received during crop growth of *Kabuli* chickpea was 220 mm, which was lower than Anwar's (2001), 260 mm.

Under full irrigation the seed yield of narrow-leaved lupin (581 g m⁻²) was significantly higher than *Kabuli* chickpea (326 g m⁻²) (Figure 4.3). Comparing yield potential of several legumes, Ayaz (2001) also concluded that narrow-leaved lupin out yielded *desi* chickpea. These results show that seed yield was closely related to TDM production. This confirms findings of Anwar (2001) in *Kabuli* chickpea, Husain *et al.* (1988a) in field bean, and Ayaz (2001) in narrow-leaved lupin. It is reasonable to assume that changes in physiological process responsible for a TDM reduction are also responsible for seed yield reduction. As noted above water stress reduces TDM production by decreasing stomatal opening, stomatal conductance and photosynthesis (Leport *et al.*, 1998; 1999). These changes may also be responsible for yield reductions under water stress. As discussed in the literature review, water stress can also increase flower, pod and seed abortion, therefore lower HI. In contrast, under full irrigation the crops did not encounter these physiological changes and thus more seeds were produced.

There was a 45 % decrease in seed yield with double irrigation (excess water) (Table 4.4). Toker *et al.* (2007) reported that seed yield of chickpea could be reduced by 100 % with waterlogging. Several physiological mechanisms are believed to be responsible for this yield reduction. Those include stomata closure (Jackson and Hall, 1987), reduced

leaf gas exchange and thus photosynthesis (Davies *et al.*, 2000b), and reduced N fixation (Bacanamwo and Purcell, 1999). Narrow-leafed lupin seed yield was reduced by 60 % when waterlogged (Davies *et al.*, 2000c). The reduction in seed yield of narrow-leafed lupin in this study was less than that reported by Davies *et al.* (2000c); this might have been because the waterlogged conditions of Davies *et al.* (2000c) might have been more severe than in this work. The plots of Davies *et al.* (2000c) were sealed with steel slides to control drainage. This method was not used in this study and the soil in the present study is well drained (New Zealand Department of Scientific and Industrial Research, 1968).

Responses to nitrogen

There are few research results indicating positive seed yield responses in *Kabuli* chickpea and narrow-leafed lupin to additional N fertilizer. Comparing the yield of mineral N supplied and N₂ fixing lupins, Ma *et al.* (1998) reported that there was no significant difference in seed yield even though there was more branch growth and biomass production from plants supplied with adequate mineral N. Consequently, crops given mineral N had a low HI (Ma *et al.*, 1998). Work on foliage spray application of N fertilizer by Seymour and Brennan (1995) also reported no response to N. The result here also showed no response in seed yield of *Kabuli* chickpea and narrow-leafed lupin to N fertilizer application. It is not possible to claim that additional N fertilizer increased vegetative growth at the expense of reproductive growth since the reduction in HI in N fertilizer plots was not significant (Table 4.4). Alternatively, it might be explained based on the results of Evans *et al.* (1987) who showed that total N in lupin was not increased by mineral N. If the additional N, in this study, did not change leaf N content as in the results of Evans *et al.* (1987), it must not have changed the carbon assimilation rate and radiation interception; hence, growth and seed yield since leaf N content strongly determines assimilation rate (Sinclair and Horie, 1989). There was no indicator of a growth rate response to N application as there was no variation in WMAGR and MGR between full irrigation and full irrigation with additional N fertilizer (Table 4.1).

Harvest index

In *Kabuli* chickpea, while there was no significant difference in crop HI among nil, half, full irrigation and control treatments, double irrigation significantly lowered the HI. In contrast, the HI of narrow-leafed lupin did not differ among half, full, double irrigation

and the control but it was significantly decreased in the nil irrigation treatment (Figure 4.4). While the *Kabuli* chickpea results agree with those of Husain *et al.* (1988a) in field bean and McKenzie (1987) in lentil, the narrow-leafed lupin result is similar to that of Dracup *et al.* (1998) and in other legumes reported by Pandey *et al.* (1984a) who found that HI was increased with irrigation. Thomas and Fukai (1995) found that while the HI of chickpea increased under water deficit conditions in two experiments, in another experiment HI decreased with water stress.

This difference in HI responses to irrigation between *Kabuli* chickpea and narrow-leafed lupin might be explained by the partitioning patterns of the two legumes. There have been results indicating that translocation of DM from vegetative plant parts could account for 30 % of pod dry weight (Khanna-Chopra and Singha, 1987). In a recent carbon (C) labelling study Davies *et al.* (2000e) showed that under water deficit conditions translocated C from vegetative parts represented 13 % of total seed C in chickpea. In this study, the dry weight of the *Kabuli* chickpea seed might be partially derived from remobilization from vegetative plant parts. Thus, the crop might be able to continue seed growth despite low vegetative growth, thereby maintaining the HI. In contrast, seed growth of narrow-leafed lupin depended less on remobilization (Palta *et al.*, 2007). The continuous growth of vegetative parts in the narrow-leafed lupin, even after flowering (Perry, 1975), might suggest high competition between vegetative and reproductive parts. Under a water deficit, where assimilate is limited, seed growth might be decreased. These factors might be responsible for the low HI of the narrow-leafed lupin under nil irrigation.

Yield components and their relationship to seed yield

Number of pods plant⁻¹

In this work there was a threefold increase in pods plant⁻¹ with full irrigation. This is typical of other results with *Kabuli* chickpea (Verghis *et al.*, 1999; Anwar, 2001), narrow-leafed lupin (Dracup *et al.*, 1998) and field bean (Husain *et al.*, 1988a). A reduction of pods plant⁻¹ was ascribed to increased pod abortion and decreased pod formation (Behboudian *et al.*, 2001). Behboudian *et al.* (2001) observed that droughted chickpea had higher pod abortion than control plants. This is consistent with the result of Dracup *et al.* (1998) who showed that while there was no difference in the number of

flower between water deficit and fully irrigated plots, the number of productive pods plant⁻¹ was reduced in the water deficit plots.

In several legume species the number of pods plant⁻¹ is strongly related to seed yield. A large body of evidence confirms this relationship (Husain *et al.*, 1988a). This work gave the same result in narrow-leafed lupin but not *Kabuli* chickpea. The non significant relationship between seed yield and pods plant⁻¹ in *Kabuli* chickpea might be attributed to yield component plasticity. As indicated in Table 4.6 and 4.7, even though the half irrigation treatment gave a lower pod number than full irrigation, seed yield did not differ between the two treatments. Seed yield in the half irrigation treatment might have been increased by increased seed weight compared with full irrigation.

Number of seeds pod⁻¹

Seed yield reduction under water stress can be attributed to pod number and seed number (Palta and Plaut, 1999). This work indicated a positive relationship between seeds pod⁻¹ and seed yield (Table 4.8). A reduction in seed number is caused by seed abortion (Dracup and Kirby, 1996a) as a reduction in seeds pod⁻¹ corresponded with an increase in failure of seed to fill (Palta and Plaut, 1999).

This work indicates that seeds pod⁻¹ in *Kabuli* chickpea was less variable among irrigation levels with an average value of 1. However, seeds pod⁻¹ were reduced by 22 % in narrow-leafed lupin (Table 4.6). Palta and Plaut (1999) also reported an 11 % reduction in seeds pod⁻¹ under water stress in narrow-leafed lupin. Dracup and Kirby (1996a) speculated that seed abortion might be caused by high temperatures and inadequate assimilates. This scenario seems obvious under water stress. There is evidence to support this speculation. Palta and Plaut (1999) suggested that leaf abscission might be responsible for reduced DM accumulation, hence, lower seed number. Dracup and Kirby (1996b) also suggested that under water deficits assimilates for seed growth might be remobilized from the leaves, which caused rapid leaf senescence and stopped further DM accumulation and plants terminated seed growth. In this study, there was a positive relationship between seeds pod⁻¹, MaxDM, and crop grow rate (Table 4.9), which suggests assimilate limitation for seed growth with no irrigation. The concept of seed growth being limited by assimilate availability was also confirmed in a shading experiment. In *Kabuli* chickpea, Verghis (1996) reported that shaded plants had a 20 % higher abortion rate than non-shaded plants.

A similar result in soybean was observed by Egli and Bruening (2001) who showed that shade reduced seed growth rate by about 50 %.

100 seed weight

There was an interaction between species and irrigation for this yield component (Table 4.7). While the 100 seed weight of *Kabuli* chickpea was reduced with full irrigation, there was no effect of irrigation level on the 100 seed weight of narrow-leaved lupin. The performance of the crops are typical of *Kabuli* chickpea (Saxena *et al.*, 1990; Anwar, 2001) and narrow-leaved lupin (Palta and Plaut, 1999). Husain *et al.* (1988a) reported an inconsistent response of seed weight to irrigation in field bean.

The reduction in the 100 seed weight of *Kabuli* chickpea with full irrigation might have been due to high pod production, leading to competition for assimilates for seed growth as there was a significantly negative ($P < 0.05$) relationship between pods plant⁻¹ and 100 seed weight (Table 4.8). This negative relationship occurs as an increase in one component can limit others as observed by Adams (1967). Anwar (2001) speculated that continuous vegetative growth might also contribute to a reduced 100 seed weight.

The reduced seed weight in unirrigated narrow-leaved lupin in this study is supported by the result of Egli and Bruening (2004) with soybean and Dapaah (1997) with pinto beans. Brocklehurst *et al.* (1978) reported that seed weight under water stress was limited by assimilate availability, which was determined by the rate of photosynthesis. In this study, assuming crop growth rate corresponded with the rate of photosynthesis; seed weight also depended on crop growth rate (Table 4.9).

Number of seeds m⁻²

Egli (1998) suggested that yield variation can be analyzed by using only seed number unit area⁻¹ and seed weight since the number of seeds unit area⁻¹ takes account of the number of plants unit area⁻¹, pods plant⁻¹ and seeds pod⁻¹. These primary components can be used to explain the relation of photosynthesis to seed yield. The rate of photosynthesis might determine seeds unit area⁻¹ and the duration of photosynthesis which determines seed size. By taking crop growth rate as an indicator of the rate of photosynthesis, there have been results which showed that the number of seeds unit area⁻¹ depends on the crop growth rate. In a shading experiment, designed to reduce photosynthesis, Jiang and Egli (1995) reported that seed size and crop growth in soybean

was significantly reduced and there was a close relationship between crop growth rate and seed number unit area⁻¹. This is consistent with the results of Egli and Zhen-wen (1991) who compared several cultivars of soybean with different growth rates.

The results indicate a close relationship between seeds m⁻² and seed yield (Table 4.8). Seeds m⁻² was also strongly related to the crop growth rate (Figure 4.5 and 4.6). This is supported by the results of Saxena *et al.* (1990) and Guilioni *et al.* (2003) who found that with various chickpea and pea cultivars, under water and heat stress, there was still a relationship between seed number and plant growth. A similar relationship was reported by Vega *et al.* (2001) in soybean, by Hawkins and Cooper (1981) in maize (*Zea mays* L.) and by Haro *et al.* (2007; 2008) in peanut (*Arachis hypogaea* L.). They also suggested that a shortage of assimilate reduced seed number. Water stress and water logging can both reduce photosynthesis through reduced stomatal conductance (Leport *et al.*, 1998; Davies *et al.*, 1999; Davies *et al.*, 2000b). Crops in this study might have had reduced photosynthesis and growth rates under water deficit (nil irrigation) and with excess water (double irrigation), which led to reductions in seed number and seed yield. In contrast, with full irrigation, the crops maintained photosynthesis and increased both seed number and seed yield. Husain *et al.* (1988a) also emphasized that the yield responses of field bean to irrigation was related to seeds unit area⁻¹, which is the result of an increase in seeds pod⁻¹ and pods unit area⁻¹.

Conclusions

1. The results indicated that growth of *Kabuli* chickpea and narrow-leafed lupin were increased by irrigation. The fully irrigated crop growth rate was 51 % higher than that in unirrigated plots. Plots receiving double irrigation had decreased crop growth rates.
2. There was a threefold increase in seed yield with full irrigation over no irrigation. Seed yield of narrow-leafed lupin responded more to irrigation than *Kabuli* chickpea. With full irrigation narrow-leafed lupin gave a seed yield of 649 g m⁻², *Kabuli* chickpea gave a seed yield of 369 g m⁻². Water logging reduced the seed yield of the two legumes by 45 % compared to full irrigation.

3. There was no response in growth and seed yields of *Kabuli* chickpea and narrow-leafed lupin to additional N fertilizer application at 150 kg ha⁻¹.
4. Seed yield was strongly correlated to TDM, seeds pod⁻¹ and seeds m⁻² for the two legumes. All yield components were strongly affected by irrigation but HI varied little within an individual legume species. Harvest index was positively related to seed yield only in narrow-leafed lupin.

Chapter 5

Effect of irrigation on canopy development and radiation interception of *Kabuli* chickpea and narrow-leafed lupin

Summary

The response of *Kabuli* chickpea (*Cicer arietinum* L.) cv. Principe and narrow-leafed lupin (*Lupinus angustifolius* L.) cv. Fest in canopy development; leaf area index (LAI), radiation interception and radiation use efficiency (RUE) to different levels of irrigation and nitrogen (N) fertilizer applied at 150 kg N ha⁻¹ at sowing was examined on a Templeton silt loam soil at Lincoln University, Canterbury, New Zealand in 2007/08. The irrigation treatments were; no irrigation, half irrigation, full irrigation, double irrigation and a control was full irrigation with N fertilizer (150 kg N ha⁻¹) applied at sowing. Irrigation increased leaf area index (LAI), leaf area duration (LAD), total intercepted PAR (photosynthetically active radiation) and final RUE. The maximum LAI of fully-irrigated *Kabuli* chickpea was 3.96 at 76 days after sowing (DAS) and that of fully-irrigated narrow-leafed lupin was 6.21 at 84 DAS. This maximum LAI was reduced in unirrigated plots to 2.32 and 2.2 for *Kabuli* chickpea and narrow-leafed lupin, respectively. Double irrigation and N fertilizer did not significantly affect LAI compared to full irrigation.

Total intercepted PAR of *Kabuli* chickpea was increased by 28 % with full irrigation from 630 (no irrigation) to 807 MJ m⁻² (full irrigation) and that of narrow-leafed lupin was also significantly increased by 33 % from 785 (no irrigation) to 1,042 MJ m⁻² (full irrigation). Accumulated intercepted PAR was linearly related to accumulated above-ground DM ($R^2 \geq 0.96^{**}$). The final RUE was significantly increased by irrigation. With full irrigation, final RUEs were 1.49 and 2.17 g DM MJ⁻¹ PAR for *Kabuli* chickpea and narrow-leafed lupin, respectively. Double irrigation decreased the final RUE of narrow-leafed lupin by 28 %. Nitrogen fertilizer did not affect final RUE. Leaf area duration, total intercepted PAR and final RUE were significantly related to above-ground DM and seed yield ($r \geq 0.55^{**}$). This suggests that irrigation increased crop growth and seed yield primarily by increasing these canopy and radiation interception attributes.

Introduction

Crop growth, development and yield are strongly affected by water deficit (Hsiao, 1973). Analysis of crop growth response to irrigation or water supply in terms of final yield is of limited use for extrapolation of the result to other locations (Gallagher *et al.*, 1983). Alternatively, crop growth and seed yield response to water supply, or other environmental factors, can be analyzed as a function of the amount of radiation intercepted and the efficiency of conversion of intercepted radiation into biomass production, i.e. the RUE (Monteith, 1977). Monteith (1977) suggested that RUE was relatively stable if crops are grown under unstressed conditions. However, RUE can be variable under water stress. As crops respond to water stress by stomatal control, stomatal restriction to minimize water losses also reduces leaf CO₂ uptake hence reducing RUE. There have been results indicating a positive RUE response to irrigation (Muchow, 1985b; Chapman *et al.*, 1993; Thomas and Fukai, 1995). In Canterbury, previous work has also indicated an increase in total intercepted PAR and RUE of grain legumes with irrigation (Husain *et al.*, 1988b; Dapaah *et al.*, 2000; Anwar *et al.*, 2003a). However, there is still a need for more information on variation in RUE in response to irrigation if a crop model for *Kabuli* chickpea and narrow-leafed lupin is to be applicable to a wide range of growing conditions.

Water logging reduces stomatal conductance (Jackson and Hall, 1987; Davies *et al.*, 2000b). This mechanism might be involved in reduced RUE as suggested by Jamieson *et al.* (1995) for water stress. Sinclair and Horie (1989) argued that RUE is a function of leaf N content. Radiation use efficiency increases with leaf N content to a saturation point. There is no further increase in RUE if the leaf N content is higher than the saturation point (Sinclair and Muchow, 1999). Application of N fertilizer increases plant N content, which might in turn lead to increased RUE.

There is limited information on the effect of water logging and N fertilizer on grain legume RUE in Canterbury. This field experiment was designed to examine variation in canopy development, radiation interception and the RUE of *Kabuli* chickpea and narrow-leafed lupin to different irrigation treatments ranging from water stress (no irrigation) to full and double full irrigation (water logging) and full irrigation with N fertilizer (150 kg N ha⁻¹).

Results

Leaf area index and leaf area duration

Significant responses to irrigation were observed from 68 DAS to near maturity in the two legumes (Figure 5.1). Averaged over irrigation level, the LAI of *Kabuli* chickpea was significantly smaller than that of narrow-leafed lupin. In *Kabuli* chickpea, non-irrigated plots reached a maximum LAI of 2.32; whilst, fully-irrigated plots reached a maximum LAI of 3.96 at 76 DAS (Figure 5.1a). There was no significant difference in LAI between full irrigation and double full irrigation. Nitrogen fertilizer only significantly increased the LAI of *Kabuli* chickpea to 5.00 at 91 DAS.

In narrow-leafed lupin, maximum LAI was reached at 84 DAS in all treatments with the exception of the unirrigated treatment. While fully-irrigated narrow-leafed lupin had a maximum LAI of 6.21, unirrigated narrow-leafed lupin had a maximum of 2.2 at 61 DAS (Figure 5.1b). The LAI with double irrigation was not significantly different from full irrigation. Nitrogen application did not affect the LAI of narrow-leafed lupin. In both legumes, LAI declined rapidly in the unirrigated treatment (Figure 5.1).

Leaf area duration was significantly affected by irrigation and the interaction between irrigation and legume species (Table 5.1). On average, over the two legumes, fully irrigated plants had a LAD of 292 days. This was 106 % higher than with no irrigation. However, the LAD with double irrigation was not significantly different from fully irrigated plots. With full irrigation, the LADs were 231 and 352 days for *Kabuli* chickpea and narrow-leafed lupin, respectively. A significant interaction showed that water deficit affected the LAD of narrow-leafed lupin more than that of *Kabuli* chickpea; whilst, the LAD of the former was reduced by 59 %, the latter was only reduced by 40 % (Table 5.2). Nitrogen fertilizer only increased the LAD of *Kabuli* chickpea (Table 5.2).

Seed yield was also positively related to LAD but the correlation coefficients were smaller than for TDM (Table 5.3). Total above-ground DM at final harvest was significantly related to the LAD in the two legumes (Figure 5.2). Variation in the LAD explained 94 % and 84 % of total above-ground DM production in *Kabuli* chickpea and narrow-leafed lupin, respectively.

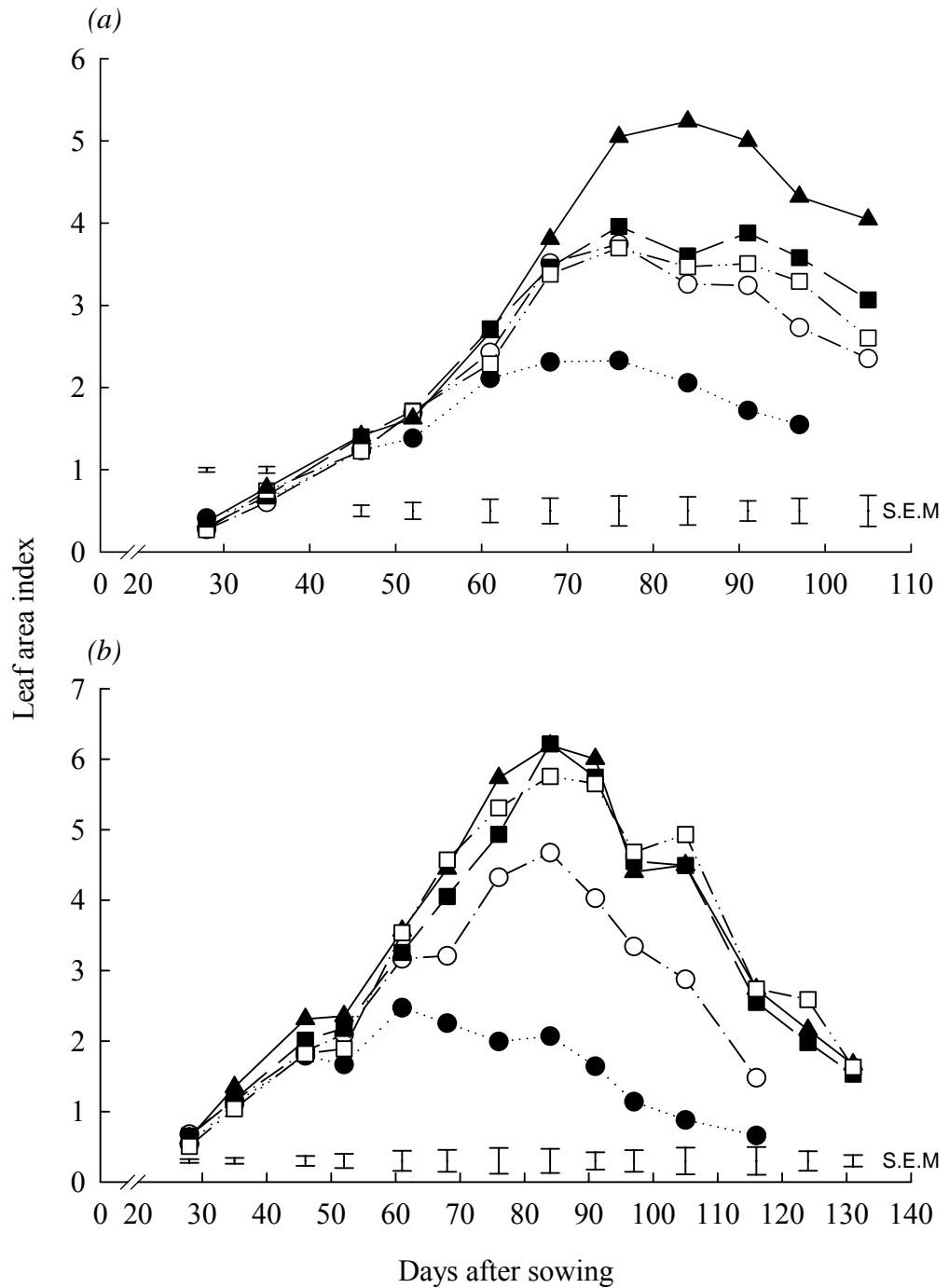


Figure 5.1. Effect of irrigation on leaf area index to physiological maturity of *Kabuli* chickpea (a) and narrow-leaved lupin (b) grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean.

Table 5.1. The effect of irrigation level and N fertilizer on the leaf area duration (LAD), total intercepted PAR, final radiation use efficiency (RUE) and the extinction coefficient (*K*) of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	LAD (days)	Total PAR (MJ m ⁻²)	Final RUE ^a (g DM MJ ⁻¹ PAR)	Extinction coefficient (<i>K</i>)
Nil	142	708	0.76	1.04
Half	231	842	1.09	1.04
Full	292	925	1.83	1.01
Double	287	907	1.30	1.02
S.E.M	16	23	0.13	0.01
Significance	***	***	***	ns
Significant trends				
Linear (I _L)	***	***	*	ns
Quadratic (I _Q)	**	***	**	ns
Species (S)				
<i>Kabuli</i> chickpea	214	765	1.27	1.04
Narrow-leaved lupin	298	962	1.51	1.01
S.E.M	5	7	0.07	0.01
Significance	***	**	*	**
Nitrogen fertilizer				
<i>Kabuli</i> chickpea at Full + N	286	819	1.92	1.01
Narrow-leaved lupin at Full + N	373	1051	2.03	1.02
Means of Full + N	330	935	1.97	1.02
Designed contrast (Full + N vs. Full)	ns	ns	ns	ns
CV %	7.7	2.2	20.1	2.20
Significant interactions				
I x S	***	**	ns	ns
I _L x S	***	**	*	ns
I _Q x S	ns	ns	ns	ns
(Full + N vs. Full) x S	ns	ns	ns	*

ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001. ^a RUE was estimated as ratio of total DM at final harvest to the total intercepted PAR.

Table 5.2. The irrigation by species interaction effect on leaf area duration (LAD), total intercepted PAR of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	LAD (days)		Total PAR (MJ m ⁻²)	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	139	145	630	785
Half	204	258	774	909
Full	231	352	807	1,042
Double	213	362	792	1,023
Full + N	286	373	819	1,051
S.E.M		18		25
Significance		***		**
CV		7.7		2.2

** = P < 0.01, *** = P < 0.001.

Table 5.3. The correlations between leaf area duration (LAD), total intercepted photosynthetically active radiation (PAR), and the radiation use efficiency (RUE) and above-ground total dry matter (TDM) at final harvest, seed yield and crop harvest index (CHI) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

	TDM	Seed yield	CHI
<i>Kabuli</i> chickpea			
LAD	0.92**	0.56*	-0.53*
Total PAR	0.80**	0.55*	-0.47
Final RUE	0.99**	0.70**	-0.43
Narrow-leafed lupin			
LAD	0.84**	0.81**	0.47
Total PAR	0.86**	0.85**	0.54*
Final RUE	0.99**	0.98**	0.42

Significance indicated by: * = P < 0.05 and ** = P < 0.01.

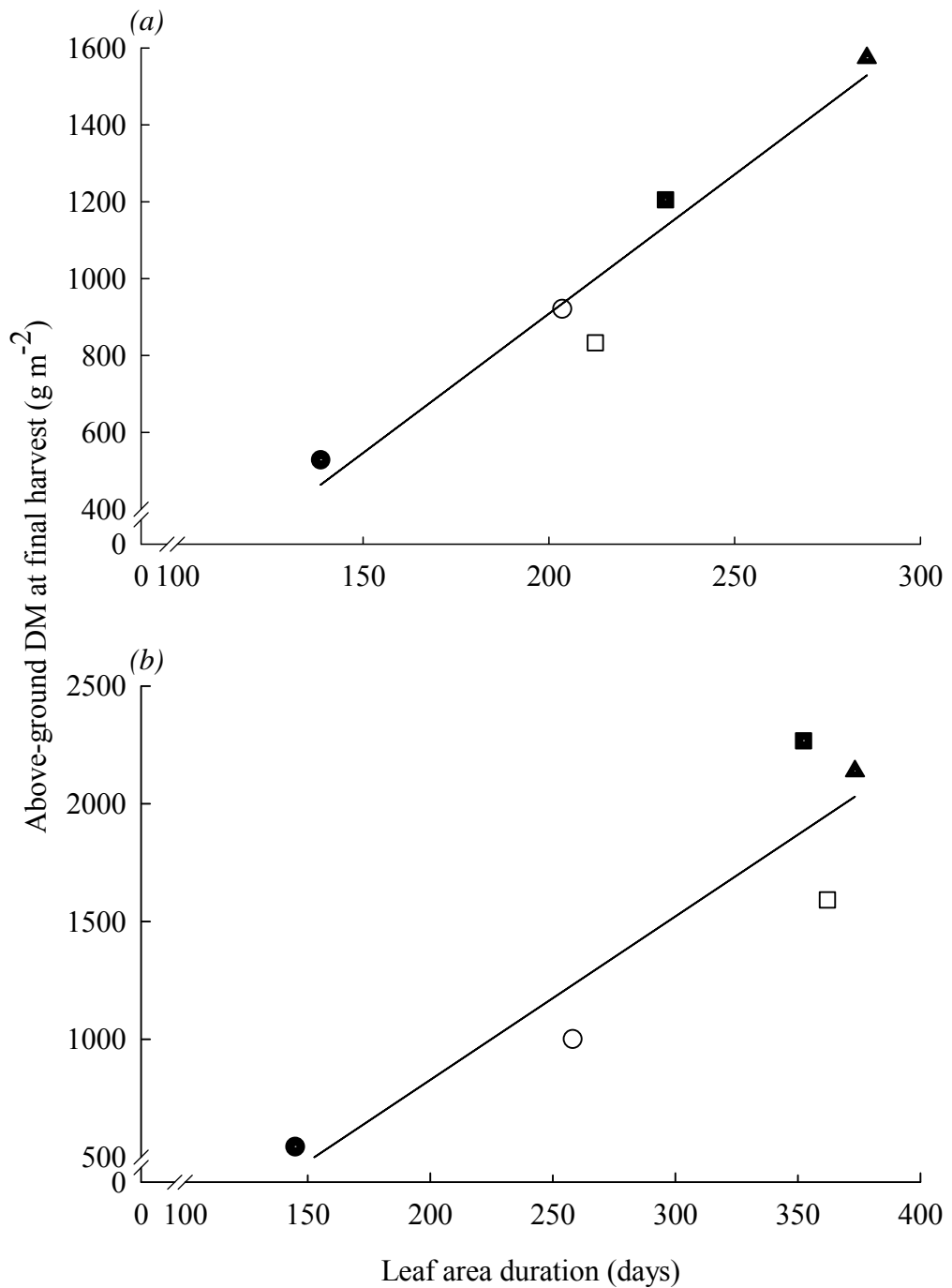


Figure 5.2. The relationship between leaf area duration and total above-ground dry matter production at final harvest of *Kabuli* chickpea (a), $Y = -540.41 + 7.24X$ ($R^2 = 0.94$), and narrow-leaved lupin (b), $Y = -559.17 + 6.93X$ ($R^2 = 0.84$), grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08.

Radiation interception

The fraction of radiation intercepted was affected by the treatments in a similar manner to LAI (Figure 5.3). Fully-irrigated *Kabuli* chickpea intercepted 98 % of total incident solar radiation when the LAI reached a maximum of 3.96 at 76 DAS. Non-irrigated *Kabuli* chickpea achieved a maximum LAI of 2.3 and the maximum fraction of radiation intercepted was 90 % of incoming incident radiation. In contrast, fully-irrigated *Kabuli* chickpea intercepted 95 % of incoming incident radiation at an LAI of 2.9. Similar responses were observed in narrow-leafed lupin. While non-irrigated narrow-leafed lupin intercepted only 90 % of incoming incident radiation, fully-irrigated narrow-leafed lupin plants intercepted 95 % of the incoming incident radiation at an LAI of 3.0. As water stress developed at later stages of crop growth, the fraction of radiation intercepted was less than 90 %. Double irrigation (water logging) did not significantly decrease the maximum fraction of radiation intercepted. Added N, at sowing, also did not significantly increase the maximum fraction intercepted. At 84 DAS fully-irrigated narrow-leafed lupin intercepted 99 % of total radiation. Double irrigation (water logging) and N application did not significantly affect the fraction of radiation intercepted. No irrigation reduced the fraction intercepted to 85 %.

Total intercepted PAR and the extinction coefficient

Total intercepted PAR varied significantly with irrigation level (Table 5.1). Averaged over the two legumes, full irrigation increased total PAR by 31 %. Total PAR was also affected by the interaction between irrigation and legume species (Table 5.2). While full irrigation increased total PAR of *Kabuli* chickpea by 28 %, the total intercepted PAR of narrow-leafed lupin was increased by 33 %. Double irrigation did not significantly reduce total intercepted PAR compared to full irrigation in the two legumes. Nitrogen applied at 150 kg N ha⁻¹ did not increase total intercepted PAR (Table 5.1). Averaged across irrigation level, *Kabuli* chickpea intercepted a total PAR of 764 MJ m⁻² and narrow-leafed lupins intercepted 921 MJ m⁻².

The extinction coefficient (*K*) was relatively stable among irrigation levels (Table 5.1). The pooled data for all irrigation treatments in each legume species are shown in Figure 5.4. Averaged over irrigation level, the *K* of narrow-leafed lupin (1.04) was significantly higher than in *Kabuli* chickpea (1.01).

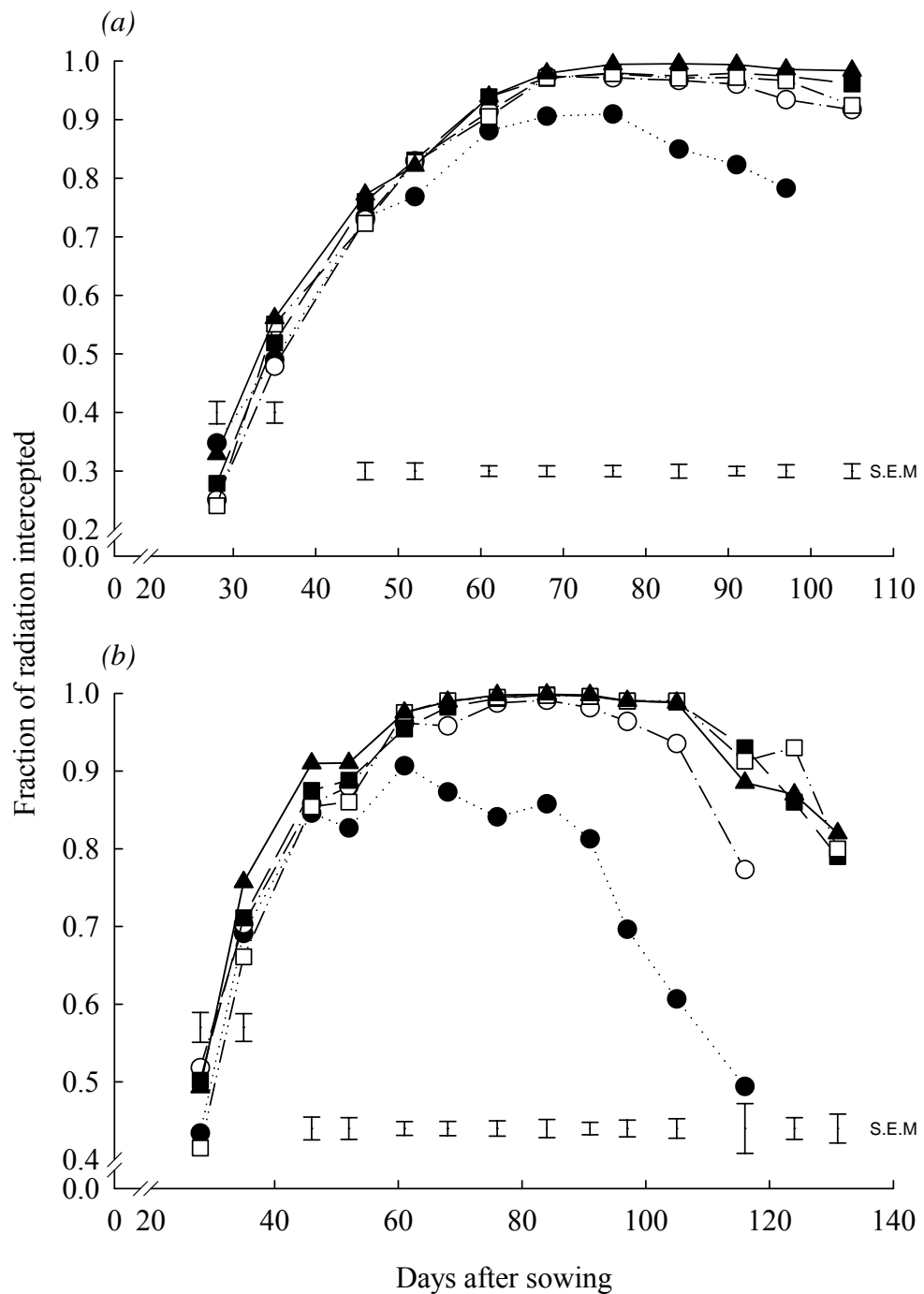


Figure 5.3. Effect of irrigations on fraction of radiation intercepted up to physiological maturity of *Kabuli* chickpea (a) and narrow-leaved lupin (b) grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean.

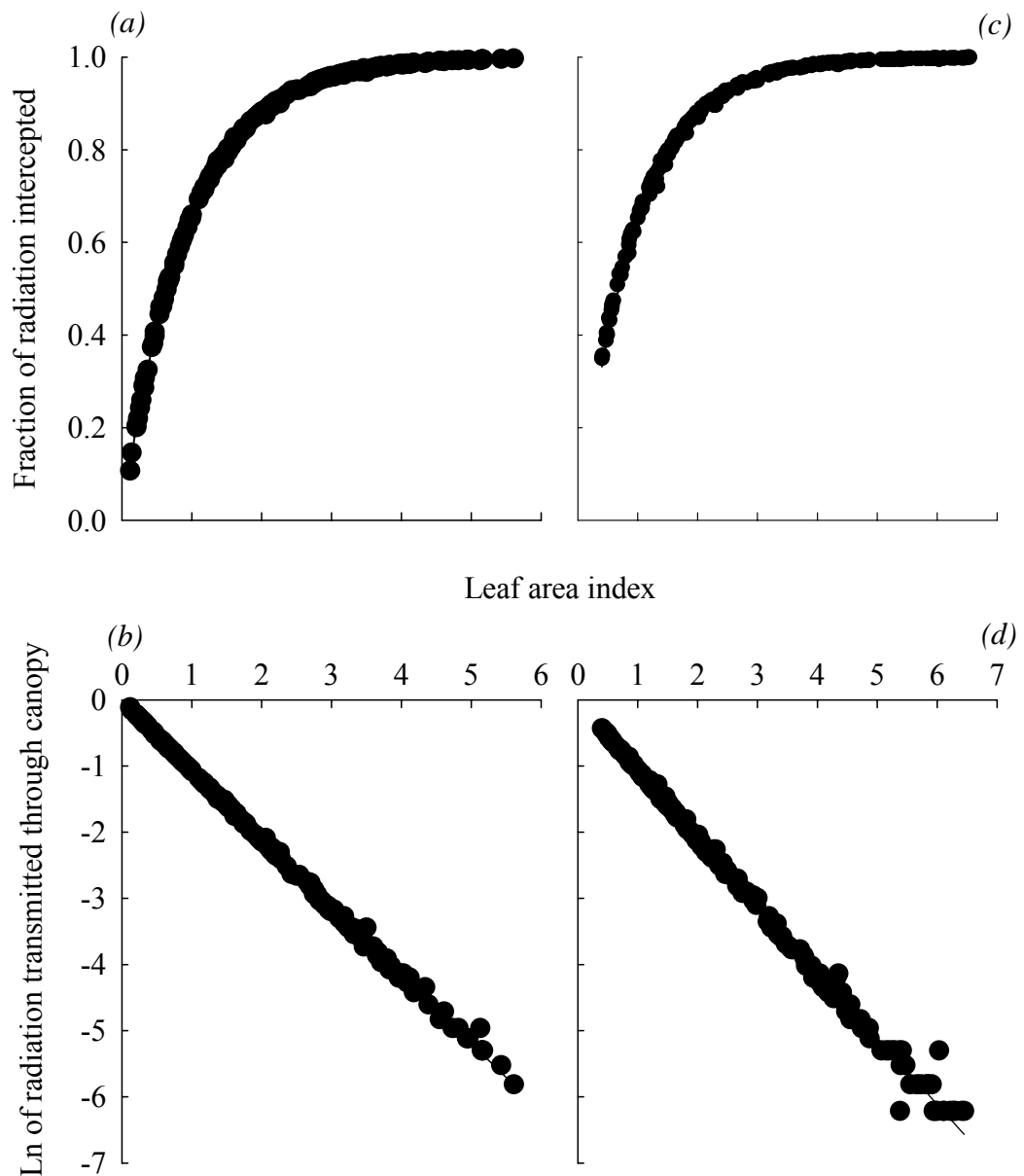


Figure 5.4. The relationship between leaf area index (LAI) and fraction of radiation intercepted. *Kabuli* chickpea (a): $Y = 1 - e^{-1.04LAI}$ ($R^2 = 0.99$) and (b): $\ln(1 - F_i)$, $Y = -0.01 - 1.04X$ ($R^2 = 0.99$). Narrow-leaved lupin (c): $Y = 1 - e^{-1.01LAI}$ ($R^2 = 0.99$) and (d): $\ln(1 - F_i)$, $Y = -0.06 - 1.01 X$ ($R^2 = 0.99$). The slopes of the regression between \ln of radiation transmitted and LAI are the extinction coefficients of *Kabuli* chickpea (a, b) and narrow-leaved lupin (c, d) grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Radiation use efficiency

The effect of irrigation, legume species, N fertilizer and all possible interactions on RUE is shown in Table 5.1. Final RUE (as the ratio of final above-ground DM at final harvest to total intercepted PAR) varied significantly among irrigation levels and legumes species. The interaction of irrigation level by legume species also significantly affected final RUE. In *Kabuli* chickpea, final RUE increased 80 % and the RUE of narrow-leafed lupin increased 216 % with full irrigation. In the no irrigation plots *Kabuli* chickpea had a RUE of 0.83 g DM MJ⁻¹ PAR; narrow-leafed lupin had an RUE of 0.69 g DM MJ⁻¹ PAR. However, with full irrigation the final RUE of *Kabuli* chickpea was 1.49 g DM MJ⁻¹ PAR and that of narrow-leafed lupin was 2.17 g DM MJ⁻¹ PAR (Table 5.4). Double irrigation did not decrease the final RUE of *Kabuli* chickpea but it decreased the final RUE of narrow-leafed lupin by 28 % compared to full irrigation (Table 5.4). Nitrogen did not significantly change the final RUE.

Radiation use efficiency, based on the slope of the linear relationship between accumulated DM and accumulated intercepted PAR, varied significantly among irrigation levels (Figure 5.5). While the RUE of *Kabuli* chickpea fell by 34 %, that of narrow-leafed lupin fell 30 % in the no irrigation plots compared to full irrigation. With full irrigation, RUE values were 2.07 and 2.50 g DM MJ⁻¹ PAR for *Kabuli* chickpea and narrow-leafed lupin, respectively (Figure 5.5). Nitrogen only increased the RUE of *Kabuli* chickpea by 28 % (Figure 5.5).

Table 5.4. The irrigation by species interaction effect on final radiation use efficiency (RUE) and the extinction coefficient (*K*) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	Final RUE (g DM MJ ⁻¹ PAR)		Extinction coefficient (<i>K</i>)	
	<i>Kabuli</i> chickpea	Narrow-leafed lupin	<i>Kabuli</i> chickpea	Narrow-leafed lupin
Nil	0.83	0.69	1.05	1.02
Half	1.07	1.10	1.04	1.03
Full	1.49	2.17	1.05	0.98
Double	1.05	1.56	1.05	1.00
Full + N	1.92	2.03	1.01	1.02
S.E.M		0.17		7.87
CV		20.1		2.2

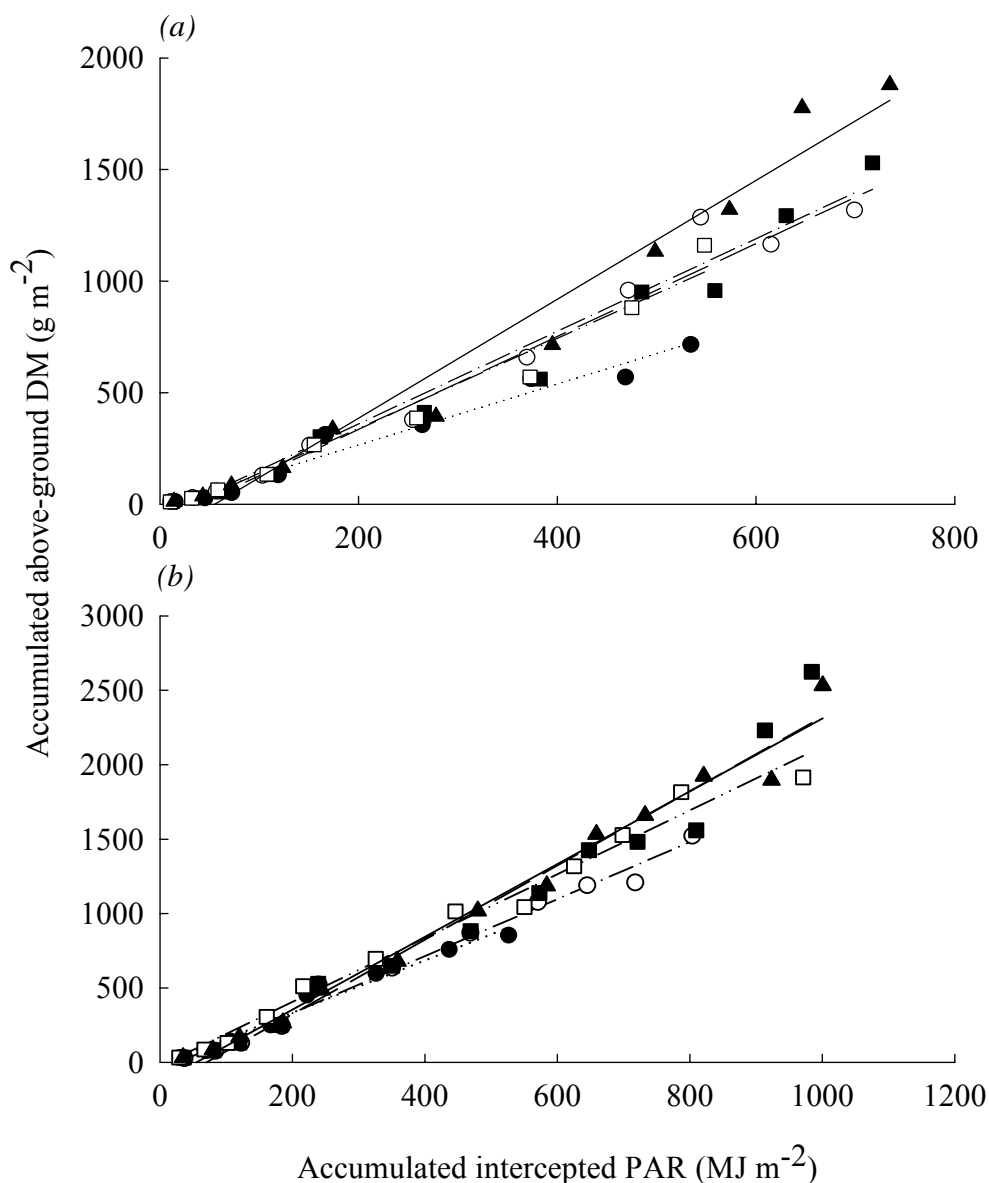


Figure 5.5. The relationship between accumulation of photosynthetically active radiation and above-ground dry matter production of two legumes grown under different irrigation regimes at Lincoln University, Canterbury, New Zealand in 2007/08. In one species, slopes preceded by *, ** and *** are significantly different from full treatment at $P < 0.05$, < 0.01 and < 0.001 , respectively.

Kabuli chickpea (a):

Nil (●, ·····), $Y = ***1.36X - 7.59$ ($R^2 = 0.96$, $n = 9$)

Half (○, - · -), $Y = 2.07X - 54.68$ ($R^2 = 0.97$, $n = 11$)

Full (■, - -), $Y = 2.07X - 80.37$ ($R^2 = 0.97$, $n = 11$)

Double (□, - · · -), $Y = 2.01X - 61.93$ ($R^2 = 0.97$, $n = 9$)

Full + N (▲, —), $Y = **2.66X - 146.87$ ($R^2 = 0.97$, $n = 11$)

Narrow-leaved lupin (b):

Nil (●, ·····), $Y = *1.75X - 18.57$ ($R^2 = 0.98$, $n = 8$)

Half (○, - · -), $Y = **1.92X - 54.09$ ($R^2 = 0.99$, $n = 11$)

Full (■, - -), $Y = 2.50X - 175.37$ ($R^2 = 0.96$, $n = 13$)

Double (□, - · · -), $Y = 2.15X - 24.84$ ($R^2 = 0.98$, $n = 12$)

Full + N (▲, —), $Y = 2.44X - 134.57$ ($R^2 = 0.98$, $n = 13$)

The relationship between total dry matter, seed yield and radiation interception

The relationships between radiation parameters and yield are shown in Table 5.3. In both species above-ground DM was positively related to LAD, total intercepted PAR and RUE. The relationship between above-ground DM and LAD and RUE in *Kabuli* chickpea was stronger than in narrow-leafed lupin. However, Total PAR was more closely related to DM in narrow-leafed lupin than in *Kabuli* chickpea. Total PAR was only related to CHI in narrow-leafed lupin. The CHI was negatively related to LAD in *Kabuli* chickpea but there was no significant relationship between LAD and CHI in narrow-leafed lupin (Table 5.3). The relationship between RUE, based on final above-ground DM, was more strongly related to above-ground DM at final harvest and seed yield than other canopy and radiation attributes (Table 5.3).

Discussion

Leaf area index and duration

Irrigation significantly increased maximum LAIs by 71 % and 182 % for *Kabuli* chickpea and narrow-leafed lupin, respectively. Similar grain legumes responses in Canterbury were reported by McKenzie, (1987); Husain *et al.* (1988b), Dapaah *et al.* (2000); and Anwar (2001). The reduction in leaf area expansion under water stress was caused by a decline in the rate of leaf production and of individual leaf area expansion (Lecoeur and Guillioni, 1998), which reflected the reduction in leaf cell division and expansion (Lecoeur *et al.*, 1995). The reduction in leaf growth at pod setting has been attributed to increased leaf senescence; leaf fall and translocation of assimilate to reproductive parts (Singh, 1991). Husain *et al.* (1988b) reported that severe water deficit accelerated senescence in field bean.

Leaf area index over time can be translated as LAD (Watson, 1947). Irrigation significantly increased LAD. The LAD was increased by 106 % with full irrigation over the unirrigated plants. The responses were similar to those reported by Anwar (2001). Positive responses of LAD to irrigation have been reported in other legumes (Husain *et al.*, 1988b; Dapaah *et al.*, 2000). Irrigation caused more rapid canopy expansion due to larger cells and more cells in leaves, early canopy closure, longer maximum LAI and delayed leaf senescence, which in turn increased the LAD (McKenzie, 1987; Husain *et al.*, 1988b). This

work confirms these results (Figure 5.1). With full irrigation, the LAD was 231 and 352 days for *Kabuli* chickpea and narrow-leaved lupin, respectively. These values are very similar to those reported by Ayaz (2001).

There was a positive relationship between LAD and above-ground TDM (Figure 5.2). However, the relationship between LAD and seed yield was not significant. A significant correlation was detected based on sample means (Table 5.3). The results of Husain *et al.* (1988b) with field bean, Dapaah *et al.* (2000) with pinto bean, Ayaz (2001) with narrow-leaved lupin and Anwar (2001) with *Kabuli* chickpea indicated the LAD was significantly related to TDM and seed yield. Herbert (1977) found no significant correlation between seed yield and the LAD of *Lupinus angustifolius*. Husain *et al.* (1988b) suggested that LAD might not provide useful information for describing growth and seed yield. Leaf area duration usually gives a good relationship with TDM if LAI does not go much above the critical LAI and LAD often gives poor estimate of seed yield because of variability in HI (McKenzie, 1987; Husain *et al.*, 1988b). Leaf area index beyond the critical LAI might decrease crop growth due to increased respiratory losses (Hay and Porter, 2006).

Radiation interception

Goudriaan and Monteith (1990) argued that the relationship between the fraction of radiation intercepted by a plant canopy and LAI can be appropriately described by an exponential function as indicated in Beer's function. These results confirm this argument (Figure 5.4). There is substantial supporting evidence (McKenzie, 1987; Husain *et al.*, 1988b; Dapaah *et al.*, 2000; Anwar, 2001; Ayaz, 2001).

The fraction of radiation intercepted differed markedly between full irrigation and no irrigation (Figure 5.3). Similar responses were reported in pinto bean by Dapaah *et al.* (2000) and in *Kabuli* chickpea by Anwar (2001). The reduction in the fraction of radiation intercepted was associated with reduced LAI and incomplete canopy closure (Dapaah *et al.*, 2000). The parallel response of LAI and the fraction of radiation intercepted to irrigation in this study support this concept. Singh (1991) also observed that a reduction in radiation interception of chickpea, under water stress, corresponded to that of LAI.

Total PAR intercepted was significantly increased with full irrigation (Table 5.2). Similar results have been reported for *Kabuli* chickpea by Singh and Sri Rama (1989) and by Anwar (2001). Before pod filling, a marked decrease in total PAR intercepted was

attributed to a reduction in new leaf production and after the pod filling stage. This reduction was caused by leaf senescence and leaf shedding (Singh and Sri Rama, 1989).

The extinction coefficient (K) was relatively stable across irrigation levels. A similar result was reported for *Kabuli* chickpea by Anwar (2001). The mean K value of *Kabuli* chickpea was 1.04, which was significantly higher than in narrow-leafed lupin at 1.01 (Table 5.1). The K value of *Kabuli* chickpea was higher than reported by Anwar (2001); however, it was similar to a value reported by Thomas and Fukai (1995) of 1.1. The K value of narrow-leafed lupin in this study was higher than that of Ayaz (2001) but similar to that of Thomson and Siddique (1997). Reversed ranks of K and RUE were observed between *Kabuli* chickpea and narrow-leafed lupin. This supports the result of Stützel and Aufhammer (1991) who found an inverse relationship between K and RUE in field bean. Hay and Porter (2006) held that K is an indicator of leaf properties which affect the penetration of PAR into the crop canopy. A crop with a high K tends to have more horizontally displayed leaves and more PAR is intercepted in upper canopy layers. This results in more light saturation and a lower RUE.

Radiation use efficiency

As reported by Leport *et al.* (1998) when a water deficit developed, photosynthesis and stomatal conductance were noticeably reduced. Sinclair and Muchow (1999) suggested this reduction decreased (RUE). There is evidence which indicates RUE is significantly reduced under water stress. In these results the final RUE was reduced by 44 % and 68 % in *Kabuli* chickpea and narrow-leafed lupin respectively with no irrigation (Table 5.4). Similar results in chickpea were reported by Anwar (2001). Working with barley (*Hordeum vulgare* L.) and chickpea, Thomas and Fukai (1995) reported that RUE sharply decreased with water stress.

The sensitivity of RUE to water stress depends on the magnitude and the time of water stress (Jamieson *et al.*, 1995; Sinclair and Muchow, 1999). Jamieson *et al.* (1995) reported that water stress, developed at an early growth stage of barley, decreased RUE, while water stress at later growth stages did not affect RUE but did affect the total amount of intercepted radiation. Singh and Sri Rama (1989), with chickpea, reached a similar conclusion. However, Muchow (1985b) reported in several grain legumes that water stress developed 6 weeks after sowing caused a greater reduction in RUE than in total intercepted PAR. In this study, water stress developed at a later growth stage. The final RUE was

significantly decreased by 44 % and 68 % and total PAR was reduced by 22 % and 25 % for *Kabuli* chickpea and narrow-leafed lupin in the no irrigation treatment, respectively (Table 5.2 and 5.4). Thomas and Fukai (1995) also reported that water stress reduced RUE in both barley and chickpea. A similar reduction in RUE in groundnut (*Arachis hypogaea* L.) was reported by Chapman *et al.* (1993) and in *Vicia faba* by Green *et al.* (1985).

Although RUE is a function of leaf N (Sinclair and Horie, 1989; Hammer and Wright, 1994), the response of RUE to leaf N is a curvilinear function. That is a response of RUE to leaf N occurs if leaf N is relatively low and a response does not occur if leaf N is high and has reached a saturation level (Sinclair and Muchow, 1999). Muchow and Sinclair (1994) found that the RUE in maize and sorghum (*Sorghum bicolor* (L.) Moench) increased with increased leaf N. However, Wright *et al.* (1993) reported that RUE of peanut was markedly increased by an increase in specific leaf N and there was no further increase in RUE when the specific leaf N content was $\geq 1.5 \text{ g N m}^{-2}$ leaf area. In this study, N fertilizer did not increase the final RUE compared to full irrigation. This might be due to a high leaf N content in both the *Kabuli* chickpea and the narrow leafed lupin. The explanation here requires further data of specific leaf N that is calculated from actual leaf area data of *Kabuli* chickpea and narrow-leafed lupin in Canterbury condition.

The final RUE, based on the ratio of final above-ground DM to total intercepted PAR, in narrow-leafed lupin was reduced by 28 % with double full irrigation compared to full irrigation. Jackson and Hall (1987) reported that in pea stomatal closure occurred 24 hours after the onset of flooding. In narrow-leafed lupin stomatal conductance was reduced by 80 % 14 days after water logging (Davies *et al.*, 2000b). These mechanisms might have contributed to the reduced final RUE in this study.

The final RUE of *Kabuli* chickpea ranged from 0.83 (no irrigation) to 1.49 g DM MJ⁻¹ PAR (full irrigation) (Table 5.4). These values are close to those of Anwar (2001). However, the final RUE of narrow-leafed lupin ranged from 0.69 (no irrigation) to 2.17 g DM MJ⁻¹ PAR (full irrigation). The values are higher than those of Ayaz (2001). This might be because of the amount N in the crops as Sinclair and Horie (1989) suggested that RUE is a function of leaf N. In this study, the amount of N in stems and leaves, at physiological maturity, was 5.63 g m⁻². The shoot N reported by Ayaz (2001) was 2.47 g m⁻².

Relationship between total dry matter, seed yield and radiation interception

Correlation analysis showed a positive relationship between above-ground DM, at final harvest, seed yield to total PAR intercepted and to RUE (Table 5.3). However, RUE (estimated as the ratio of above-ground DM at final harvest to total PAR) was more strongly related to DM and seed yield in both *Kabuli* chickpea and narrow-leafed lupin. This suggests that increases in DM and seed yield, in this study, in response to irrigation might be through increased RUE. Similar results were reported by Muchow (1985b) for soybean (*Glycine max* L.) and pigeon pea (*Cajanus cajan* L.); by Thomas and Fukai (1995) for barley and chickpea; and by Jamieson *et al.* (1995) for barley.

Conclusions

1. Full irrigation significantly increased both LAI and LAD. Maximum LAI in fully-irrigated plots was 3.96 and 6.21 for *Kabuli* chickpea and narrow-leafed lupin respectively. Averaged over the two legumes there was a more than twofold increase in LAD with full irrigation.
2. While total PAR of narrow-leafed lupin was increased by 33 % with full irrigation, that of *Kabuli* chickpea was only increased by 28 %.
3. There was a threefold increase in final RUE in narrow-leafed lupin; whilst the final RUE of *Kabuli* chickpea increased 80 % with full irrigation. With full irrigation, final RUEs were 1.49 and 2.17 g DM MJ⁻¹ PAR for *Kabuli* chickpea and narrow-leafed lupin. Final RUE of narrow-leafed lupin was not affected by N fertilizer but was decreased by 28 % with double full irrigation.
4. Leaf area index, LAD, total intercepted PAR and RUE were related to DM and seed yield.

Chapter 6

Effect of irrigation on nitrogen accumulation and partitioning in *Kabuli* chickpea and narrow-leafed lupin

Summary

A field experiment was conducted at Lincoln University, Canterbury, New Zealand in 2007/08 to determine the effect of irrigation and nitrogen application (150 kg N ha^{-1} at sowing) on variation in nitrogen (N) concentration in different plant parts, total N accumulation, nitrogen accumulation efficiency (NAE) and nitrogen harvest index (NHI) of *Kabuli* chickpea (*Cicer arietinum* L.) cv. Principe and narrow-leafed lupin (*Lupinus angustifolius* L.) cv. Fest.

At first flowering, irrigation did not significantly affect leaf N concentration of the two legumes. Leaf N concentrations at first flowering were 4.6 and 3.4 % for *Kabuli* chickpea and narrow-leafed lupin, respectively. Leaf N concentration of the two legumes was reduced by physiological maturity. Leaf N concentration of narrow-leafed lupin was not affected by irrigation or N fertilizer but was reduced to 1.15 % at physiological maturity. In contrast, leaf N concentration of *Kabuli* chickpea was affected by irrigation and by N fertilizer. With full irrigation, leaf N concentration of *Kabuli* chickpea was 1.5 %. This was reduced to 1.2 % with half irrigation and increased to 2.4 % at full irrigation with N fertilizer application. Seed N concentration in narrow-leafed lupin was also not affected by irrigation or N fertilizer (average 4.8 %). However, seed N concentration of *Kabuli* chickpea increased from 2.6 % with full irrigation to 3.9 and 3.6 % with no irrigation and with full irrigation plus N fertilizer, respectively.

Total N accumulation (based on above-ground N including N in shed leaves, roots and nodules) of narrow-leafed lupin was reduced by 75 % with no irrigation and by 25 % with double irrigation compared to full irrigation with a total N content of 45.9 g m^{-2} . As total N in *Kabuli* chickpea was entirely dependent on soil N uptake, total N in *Kabuli* chickpea was not affected by irrigation but was increased by 90 % by N fertilizer. With full irrigation, total N in *Kabuli* chickpea was 17.7 g m^{-2} . Nitrogen accumulation efficiency of narrow-leafed lupin was not affected by irrigation or by N fertilizer. At full irrigation, NAE of narrow-leafed lupin was $0.017 \text{ g N g}^{-1} \text{ DM}$. However, the NAE of *Kabuli* chickpea

ranged from 0.013 (full irrigation) to 0.020 (nil irrigation) and 0.017 g N g⁻¹ DM (full irrigation with N fertilizer).

The nitrogen harvest index (based on above-ground N including N in shed leaves) of *Kabuli* chickpea was relatively stable across irrigation levels. However, the NHI of narrow-leafed lupin fell from 0.65 with full irrigation to 0.45 with no irrigation. As NHI was less affected by irrigation than total N accumulated, a focus on increased seed N content by improving total N accumulation by full irrigation might be more important than improving the NHI. Further, there was a close relationship between total DM and total N accumulated and seed N and total N accumulated. Hence, irrigation to increase growth and seed yield might also increase N accumulation; particularly, of symbiotically fixed N.

Introduction

Grain legumes have the potential to improve nitrogen (N) availability in mixed cropping systems in New Zealand (White and Hill, 1999). McKenzie *et al.* (2001) reported that incorporation of the roots and straw of narrow leafed lupin, lentil and peas produced higher yields of ryegrass than fallow or a preceding barley (*Hordeum vulgare* L.) crop. Incorporating only roots and stems or whole plants of narrow-leafed lupin gave a yield of Italian ryegrass which was 4 % and 18 %, respectively higher than with 200 kg N ha⁻¹ (McKenzie *et al.*, 2001).

Chalk (1998) suggested that the N benefit of grain legumes to the cropping systems might be derived from direct transfer of symbiotically-fixed N, spared N during legume growth and less N immobilization during decomposition of legume residues which might be due to a low C:N ratio (Cameron, 1992; McLaren and Cameron, 1996). Dynamic crop modelling should extend to take account of the N economy of legumes in cropping systems to evaluate the impact of legumes on the system and on crop productivity (Robertson *et al.*, 2000). To achieve this, Jamieson *et al.* (2006) proposed a crop simulation model as crops are both the source of N and the biggest N sink.

Grain legumes are hypothesized as “self-destructive crops” (Sinclair and de Wit, 1976). During seed development, seeds require large amounts of N and N need is met by translocation from vegetative parts. The N loss from vegetative parts results in a cessation of physiological activity and the crop becomes senescent. Self-destruction can also affect seed yield (Sinclair and de Wit, 1976). Evans (1982) also warned that remobilization of N

from vegetative parts to seed can reduce the N in legume residue; hence, the N economy of cropping systems, where legumes are rotated with non-legume crops, is also affected.

Grain legumes contribute positively to soil N when they have high N accumulation, a high proportion of N fixed to total N, and a low nitrogen harvest index (NHI). These parameters are strongly affected by agronomic factors, symbiotic fixation and legume species (Chalk, 1998). In Canterbury, working with different legume species, Ayaz (2001) reported significant differences in total N accumulation and NHIs at various plant densities and sowing depths. There is little information on the effect of irrigation on N accumulation, N concentration or the NHI of grain legume in Canterbury. Research elsewhere indicated these N attributes are significantly affected by water supply in several legume species (Chapman and Muchow, 1985; De Vries *et al.*, 1989).

A field experiment was conducted at Lincoln University, Canterbury, New Zealand in 2007/08 to test the effect of irrigation levels ranging from no irrigation (water deficit) to double irrigation (excess water) and full irrigation with and without N fertilizer applied at sowing.

The objectives of this study were:

1. To examine variation in N concentration in plant parts under different irrigation treatments and with N fertilizer.
2. To examine variation in total N accumulation in *Kabuli* chickpea and narrow-leafed lupin in response to different irrigation levels and with the additional N fertilizer.
3. To determine the effect of irrigation and N fertilizer on the NHI of *Kabuli* chickpea and narrow-leafed lupin.

Results

Nitrogen concentration

At first flowering (48 and 64 DAS for *Kabuli* chickpea and narrow-leafed lupin, respectively), the leaf and stem N concentration were not significantly affected by either irrigation or added N fertilizer (Table 6.1). However, there was a significant difference in the N concentration between *Kabuli* chickpea and narrow-leafed lupin. While the N concentration in stem and leaf of *Kabuli* chickpea was 1.4 and 4.6 %, the concentration in stems and leaves of narrow-leafed lupin were 0.8 and 3.4 %. Added N fertilizer only increased the N concentration in stems and leaves of *Kabuli* chickpea (Figure 6.1).

At first pod set (58 and 78 DAS for *Kabuli* chickpea and narrow-leafed lupin, respectively), there was again no significant difference in leaf N concentration of *Kabuli* chickpea among irrigation levels (Figure 6.1). However, the N concentration of narrow-leafed lupin was significantly higher in the no irrigation than in the full irrigation treatment (Figure 6.2). Leaf N concentration of the two legumes was not affected by irrigation level but was significantly increased by N fertilizer ($P < 0.05$). Averaged across irrigation levels leaf N concentration of narrow-leafed lupin (3.6 %) was higher than in *Kabuli* chickpea (3.3 %) (Table 6.2).

Stem and leaf N concentration in the two legumes decreased significantly at physiological maturity (94 DAS for unirrigated *Kabuli* chickpea, 111 DAS for *Kabuli* chickpea with half, full, double irrigation and full irrigation with N, 113 DAS for unirrigated and half irrigated narrow-leafed lupin and 130 DAS for narrow-leafed lupin with full, double irrigation and full irrigation with N) (Figure 6.1 and 6.2). Mean leaf N concentration decreased to 1.7 % and 1.4 % in *Kabuli* chickpea and narrow-leafed lupin, respectively. There was a significant interaction between irrigation and legume species on leaf N concentration at physiological maturity. While the N concentration in narrow-leafed lupin did not vary among irrigation levels, the N concentration of *Kabuli* chickpea with half irrigation was the lowest (Figure 6.1). The N concentration of shed leaves (1.7 %) was not affected by irrigation, legume species or N fertilizer (Table 6.3).

Root N concentration tended to increase at physiological maturity in narrow-leafed lupin (Figure 6.2); whilst, in *Kabuli* chickpea, increased N concentration, in roots, was observed with no irrigation, full irrigation and full irrigation + N treatments (Figure 6.1). Root N concentration, at physiological maturity was not affected by irrigation level or N fertilizer. However, root N concentration differed significantly between the two legumes. The N concentration in *Kabuli* chickpea was 1.3 % (Figure 6.1) and in narrow-leafed lupin it was 2 % (Figure 6.2).

Seed N concentration was affected by irrigation (Table 6.3). Plants with no irrigation had the highest seed N concentration. The interaction of irrigation by species also affected seed N concentration. While N concentration in narrow-lupin seed was relatively stable across irrigation levels, seed N concentration in *Kabuli* chickpea was higher with no irrigation. Nitrogen fertilizer only increased seed N concentration in *Kabuli* chickpea (Table 6.4).

Table 6.1. The effect of irrigation level and N fertilizer on the nitrogen concentration (% in organ dry matter) at first flowering¹ of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Stems and branches	Green leaves
Nil	1.24	2.51	1.22	3.97
Half	1.26	3.88	1.16	4.08
Full	1.11	3.32	1.09	3.97
Double	1.10	3.30	0.95	3.65
S.E.M	0.10	0.14	0.10	0.25
Significance	ns	**	ns	ns
Significant trends				
Linear (I _L)	ns	ns	ns	ns
Quadratic (I _Q)	ns	**	ns	ns
Species (S)				
<i>Kabuli</i> chickpea	1.27	NA	1.45	4.68
Narrow-leaved lupin	1.13	3.24	0.87	3.49
S.E.M	0.05	NA	0.05	0.10
Significance	ns	NA	***	***
Nitrogen fertilizer				
<i>Kabuli</i> chickpea at Full + N	1.47	NA	1.84	5.48
Narrow-leaved lupin at Full + N	1.15	3.21	0.91	4.00
Means of Full + N	1.31	NA	1.38	4.74
Designed contrast (Full + N vs. Full)	ns	ns	ns	ns
CV %	16.2	9.6	15.1	9.9
Significant interactions				
I x S	ns	NA	ns	*
I _L x S	ns	NA	ns	**
I _Q x S	ns	NA	ns	ns
(Full + N vs. Full) x S	ns	NA	*	ns

¹ First flowering stages were 48 and 64 days after sowing for *Kabuli* chickpea and narrow-leaved lupin, respectively. ^a the data were available for lupin only, ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001, NA = unavailable data for comparison.

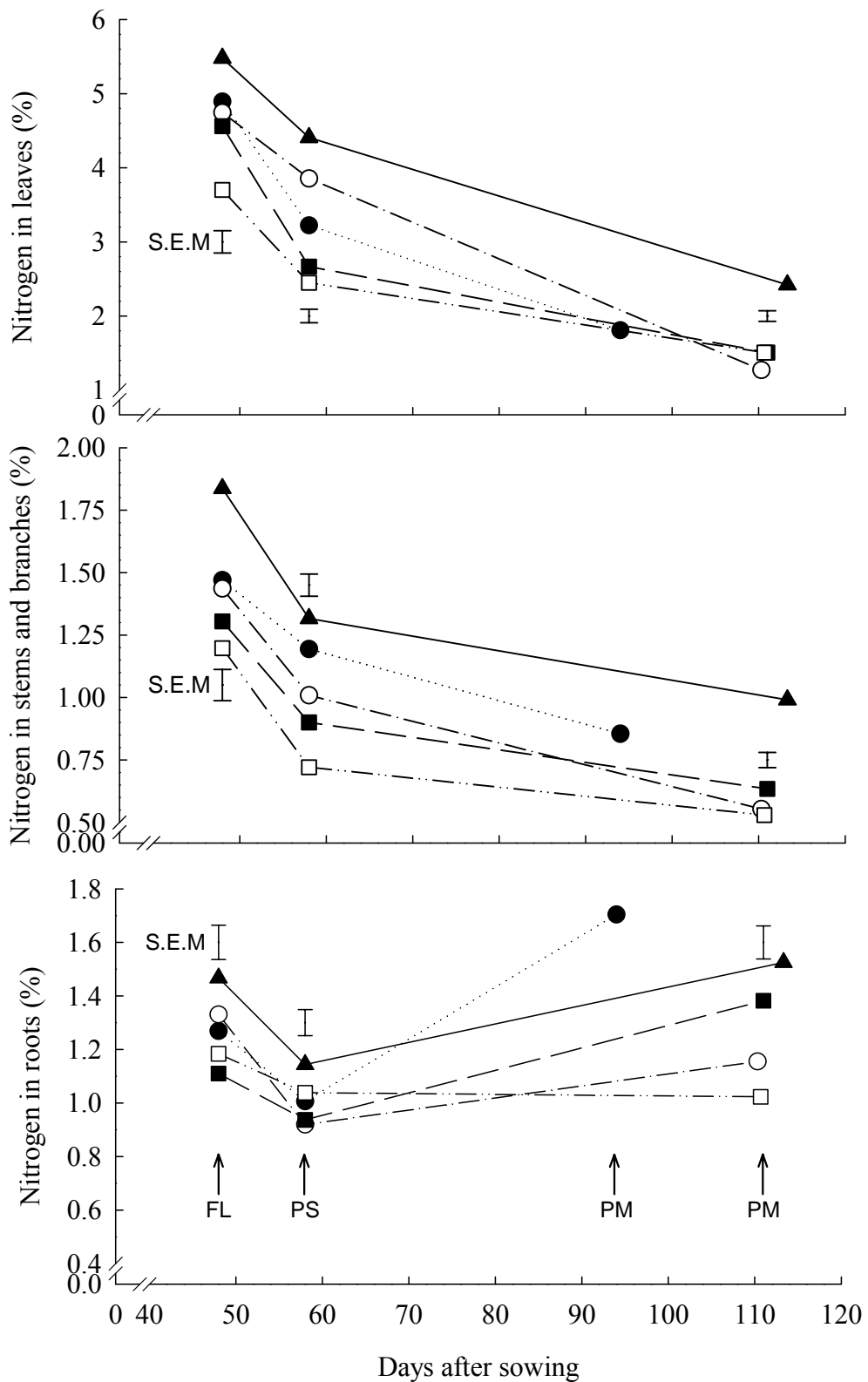


Figure 6.1. Nitrogen concentration in plant parts of *Kabuli* chickpea grown under different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean. The arrows indicate plant growth stages, FL = first flowering, PS = first pod set and PM = physiological maturity.

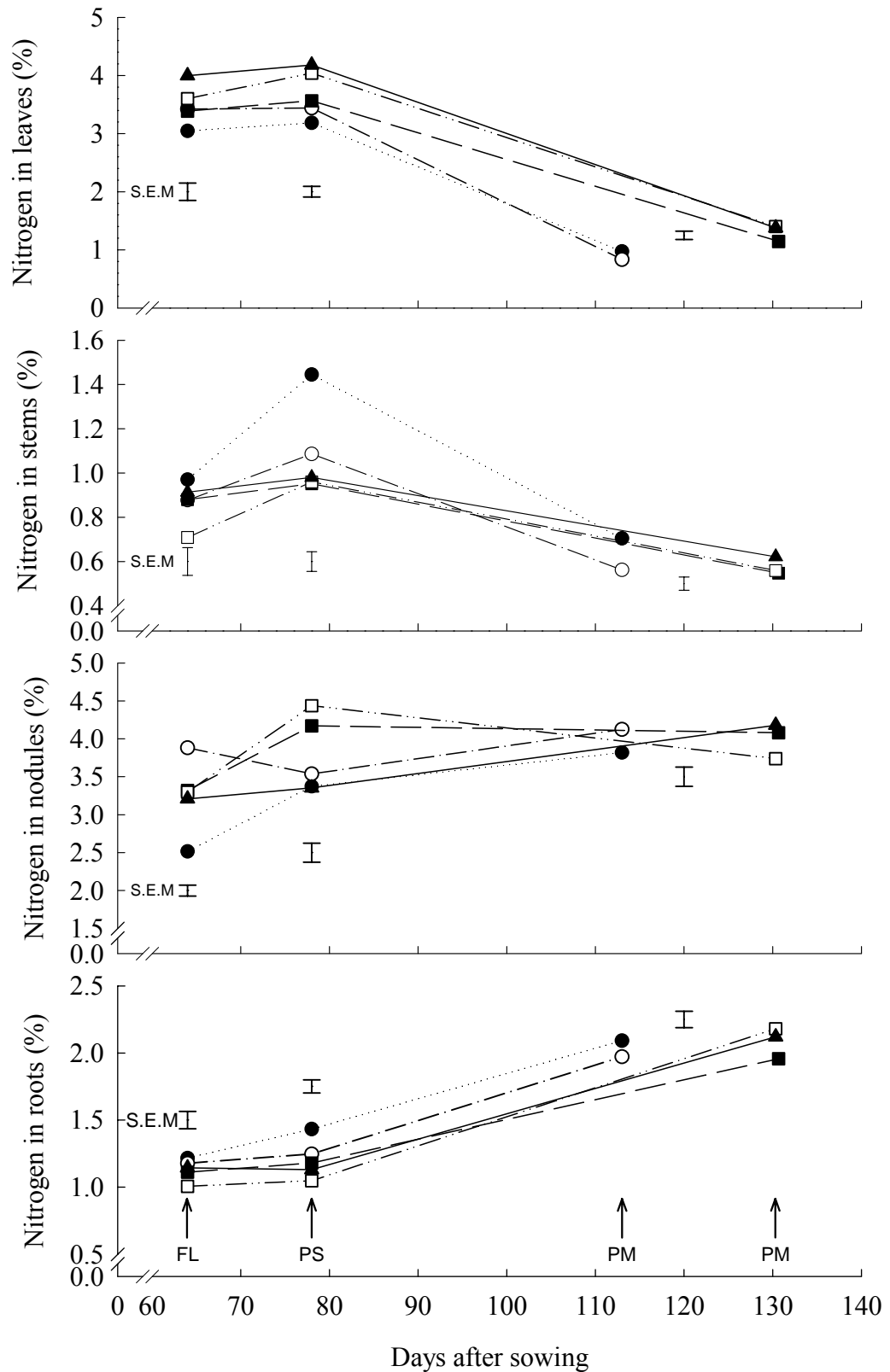


Figure 6.2. The nitrogen concentration in plant parts of narrow-leaved lupin at different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand, in 2007/08. S.E.M. = standard error of mean. The arrows indicate plant growth stages, FL = first flowering, PS = first pod set and PM = physiological maturity.

Table 6.2. The effect of irrigation level and N fertilizer application on the nitrogen concentration (% in organ dry matter) at first pod set¹ of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Stems and branches	Green leaves	Pod walls and seeds
Nil	1.22	3.37	1.32	3.20	4.26
Half	1.08	3.54	1.05	3.65	2.92
Full	1.06	4.17	0.93	3.12	3.06
Double	1.04	4.44	0.84	3.24	3.17
S.E.M	0.08	0.25	0.05	0.16	0.10
Significance	ns	ns	***	ns	***
Significant trends					
Linear (I _L)	ns	*	***	ns	***
Quadratic (I _Q)	ns	ns	*	ns	***
Species (S)					
<i>Kabuli</i> chickpea	1.01	NA	1.03	3.32	2.60
Narrow-leafed lupin	1.21	3.78	1.08	3.68	3.96
S.E.M	0.04	NA	0.05	0.05	0.18
Significance	***	NA	ns	***	***
Nitrogen fertilizer					
<i>Kabuli</i> chickpea at Full + N	1.14	NA	1.32	4.41	2.66
Narrow-leafed lupin at Full + N	1.13	3.35	0.98	4.18	3.26
Means of Full + N	1.14	NA	1.15	4.29	2.96
Designed contrast (Full + N vs. Full)	ns	ns	*	***	ns
CV %	13.7	16	17.5	5.9	20.9
Significant interactions					
I x S	ns	NA	ns	***	ns
I _L x S	ns	NA	ns	***	ns
I _Q x S	ns	NA	ns	ns	ns
(Full + N vs. Full) x S	ns	NA	ns	***	ns

¹ First pod set stages were 58 and 78 days after sowing for *Kabuli* chickpea and narrow-leafed lupin, respectively. ^a the data were available for lupin only, ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001, NA = unavailable data for comparison.

Table 6.3. The effect of irrigation level and N fertilizer application on the nitrogen concentration (% in organ dry matter) at physiological maturity¹ of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Shed leaves	Stems and branches	Green leaves	Pod walls	Seeds
Nil	1.90	3.82	1.56	0.78	1.39	0.68	4.31
Half	1.56	4.12	1.53	0.56	1.05	0.56	3.84
Full	1.67	4.08	1.69	0.59	1.33	0.59	3.69
Double	1.60	3.74	1.71	0.54	1.45	0.66	3.51
S.E.M	0.09	0.26	0.18	0.04	0.11	0.03	0.15
Significance	ns	ns	ns	**	**	ns	*
Significant trends							
Linear (I _L)	ns	ns	ns	**	ns	ns	**
Quadratic (I _Q)	ns	ns	ns	*	ns	ns	ns
Species (S)							
<i>Kabuli</i> chickpea	1.36	NA	1.73	0.71	1.70	0.76	3.05
Narrow-leaved lupin	2.06	3.99	1.73	0.60	1.15	0.55	4.83
S.E.M	0.05	NA	0.06	0.03	0.06	0.03	0.08
Significance	***	NA	ns	*	***	***	***
Nitrogen fertilizer							
<i>Kabuli</i> chickpea at Full + N	1.53	NA	2.49	0.99	2.42	1.00	3.61
Narrow-leaved lupin at Full + N	2.12	4.18	1.80	0.62	1.38	0.53	5.09
Means of Full + N	1.82	NA	2.15	0.81	1.90	0.77	4.35
Designed contrast (Full + N vs. Full)	ns	ns	ns	**	**	**	*
CV %	11.6	16.3	13.1	17	15.9	18.6	7.6
Significant interactions							
I x S	ns	NA	ns	ns	*	ns	**
I _L x S	*	NA	ns	ns	*	ns	***
I _Q x S	ns	NA	ns	ns	ns	ns	*
(Full + N vs. Full) x S	ns	NA	*	ns	*	ns	ns

¹ Physiological maturity stages were 94 days after sowing (DAS) for unirrigated *Kabuli* chickpea, 111 DAS for *Kabuli* chickpea with half, full, double irrigation and full irrigation with N, 113 DAS for unirrigated and half irrigated narrow-leaved lupin and 130 DAS for narrow-leaved lupin with full, double irrigation and full irrigation with N. ^a the data were available for lupin only, ns = non-significant, * = P < 0.05, ** = P < 0.01 and *** = P < 0.001, NA = unavailable data for comparison.

Table 6.4. The irrigation by species interaction effect on N concentration in pod walls and seeds of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level	Pod walls (%)		Seeds (%)	
	<i>Kabuli</i> chickpea	Narrow-leaved lupin	<i>Kabuli</i> chickpea	Narrow-leaved lupin
Nil	0.73	0.62	3.98	4.64
Half	0.61	0.52	2.82	4.87
Full	0.69	0.49	2.66	4.72
Double	0.74	0.58	2.19	4.83
Full + N	1.00	0.53	3.61	5.09
S.E.M		0.06		0.19
Significance		ns		*
CV		18.6		7.6

ns = non-significant, * = $P < 0.05$.

Nitrogen accumulation

Although total N did not differ significantly among irrigation levels at first flowering (48 and 64 DAS for *Kabuli* chickpea and narrow-leaved lupin, respectively) (Table 6.5) or at first pod set (58 and 78 DAS for *Kabuli* chickpea and narrow-leaved lupin, respectively) (Table 6.6), there were marked differences at physiological maturity (Table 6.7). Averaged over the two legumes, full irrigation gave the highest N accumulation at physiological maturity (94 DAS for unirrigated *Kabuli* chickpea, 111 DAS for *Kabuli* chickpea with half, full, double irrigation and full irrigation with N, 113 DAS for unirrigated and half irrigated narrow-leaved lupin and 130 DAS for narrow-leaved lupin with full, double irrigation and full irrigation with N), 31.8 g m^{-2} . In non-irrigated plots, there was only 11.6 g m^{-2} . Accumulated N was reduced by 30 % with double irrigation compared to full irrigation.

There was a significant effect of added N fertilizer at sowing on total accumulated N at first pod set (Table 6.6). The designed contrast between full irrigation and full irrigation with N fertilizer at 150 kg N ha^{-1} showed that additional N increased total N by 31 % at first pod set.

Total N assimilated in narrow-leaved lupin was significantly higher than in *Kabuli* chickpea at flowering (Table 6.5), at first pod set (Table 6.6) and at physiological maturity (Table 6.7). Narrow-leaved lupin assimilated 80 % more N than *Kabuli* chickpea at

physiological maturity. Assimilation in the lupin averaged across irrigation treatments was 31.9 g m^{-2} and that in *Kabuli* chickpea was 17.5 g m^{-2} .

Total N accumulated at physiological maturity was significantly affected by the interaction between irrigation level and legume species (Table 6.7). While the total amount of N in *Kabuli* chickpea was not affected by irrigation level, values in narrow-leafed lupin varied significantly. Fully-irrigated narrow-leafed lupin had the highest N (45.9 g m^{-2}) level but non-irrigated lupin had the lowest (11.2 g m^{-2}). Double irrigation reduced N accumulation by 24 % compared to full irrigation (Figure 6.3).

An interaction between added N fertilizer and legume species on total N was also detected (Table 6.7). Total N in *Kabuli* chickpea in the control plots (full irrigation + 150 kg N ha^{-1}) was nearly twice as high as under full irrigation. Fully-irrigated *Kabuli* chickpea assimilated 17.7 g N m^{-2} whilst fully-irrigated *Kabuli* chickpea with N fertilizer assimilated 33.5 g N m^{-2} . However, added N fertilizer did not significantly increase total N accumulated, at physiological maturity, in narrow-leafed lupin (Figure 6.3). The total N in narrow-leafed lupin at full irrigation with N fertilizer was 46.5 g m^{-2} .

Nitrogen in different plant parts

In the two legumes, at first flowering (48 and 64 DAS for *Kabuli* chickpea and narrow-leafed lupin, respectively) leaf N was the majority of total N in the crops regardless of irrigation effect (Figure 6.4 and 6.5) Averaged across irrigation levels, *Kabuli* chickpea leaf N was 76 % and leaf N in lupin was 70 % of total crop N at first flowering (Table 6.5). However, there was a trend for a reduction in these values. At physiological maturity, leaf N accounted for 15 % and 4 %, of total N in *Kabuli* chickpea and narrow-leafed lupin, respectively (Table 6.7). There was no significant difference among irrigation levels in leaf N at first flowering and first pod set (Table 6.5 and 6.6). However, the amount of leaf N differed significantly among irrigation levels at physiological maturity (Table 6.7). Full irrigation gave the highest at 2.5 g m^{-2} for *Kabuli* chickpea (Figure 6.4) and 1.6 g m^{-2} for narrow-leafed lupin (Figure 6.5). Leaf N at physiological maturity was only increased by added N fertilizer in *Kabuli* chickpea. Double irrigation did not significantly reduce leaf N in either legume.

Stem N followed the same trend as leaf N. There was a reduction in the contribution to total N over time (Figure 6.4 and 6.5). Stem N at physiological maturity was significantly affected by the interaction between irrigation level and legume species.

Table 6.5. Effect of irrigation level and N fertilizer application on the nitrogen content (g m^{-2}) at first flowering¹ of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Shed leaves ^a	Stems and branches	Green leaves	Total N
Nil	0.59	0.20	0.35	2.77	10.52	12.87
Half	0.63	0.49	0.62	3.28	9.26	12.88
Full	0.93	0.72	0.95	3.23	10.32	16.29
Double	0.70	0.86	0.36	2.90	9.84	14.05
S.E.M	0.13	0.16	0.27	0.60	1.50	1.84
Significance	ns	*	ns	ns	ns	ns
Significant trends						
Linear (I_L)	ns	*	ns	ns	ns	ns
Quadratic (I_Q)	ns	ns	ns	ns	ns	ns
Species (S)						
<i>Kabuli</i> chickpea	0.54	NA	NA	1.94	7.74	10.23
Narrow-leaved lupin	0.98	0.49	0.53	4.64	13.36	19.07
S.E.M	0.07	NA	NA	0.33	0.69	0.80
Significance	**	NA	NA	***	***	***
Nitrogen fertilizer						
<i>Kabuli</i> chickpea at Full + N	0.89	NA	NA	2.78	10.24	13.91
Narrow-leaved lupin at Full + N	1.03	0.19	0.38	5.78	15.42	20.40
Means of Full + N	0.96	NA	NA	4.28	12.83	17.15
Designed contrast (Full + N vs. Full)	ns	*	ns	ns	ns	ns
CV %	34.7	61.4	186.5	38.7	25.3	21.1
Significant interactions						
I x S	ns	NA	NA	ns	ns	ns
I_L x S	ns	NA	NA	ns	ns	*
I_Q x S	ns	NA	NA	ns	ns	ns
(Full + N vs. Full) x S	ns	NA	NA	ns	ns	ns

¹ First flowering stages were 48 and 64 days after sowing for *Kabuli* chickpea and narrow-leaved lupin, respectively. ^a data for lupin only, ns = non-significant, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$ and NA = data not available for comparison. Shed leaf data were cumulative totals.

Table 6.6. Effect of irrigation level and N fertilizer application on nitrogen content (g m⁻²) at first pod set¹ of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Shed leaves	Stems and branches	Green leaves	Pod walls and seeds	Total N
Nil	0.97	0.32	0.39	5.62	9.50	1.86	18.49
Half	0.85	0.42	0.68	5.42	10.65	1.55	19.35
Full	0.93	0.95	0.88	4.74	9.99	0.92	17.94
Double	0.78	0.69	0.71	4.54	9.17	0.73	16.27
S.E.M	0.08	0.10	0.20	0.57	0.77	0.13	1.35
Significance	ns	*	ns	ns	ns	**	ns
Significant trends							
Linear (I _L)	ns	ns	ns	ns	ns	***	ns
Quadratic (I _Q)	ns	ns	ns	ns	ns	ns	ns
Species (S)							
<i>Kabuli</i> chickpea	0.51	NA	0.09	3.67	6.47	1.74	12.49
Narrow-leafed lupin	1.22	0.54	1.28	6.99	15.04	0.72	25.75
S.E.M	0.06	NA	0.12	0.30	0.36	0.11	0.75
Significance	***	NA	***	***	***	***	***
Nitrogen fertilizer							
<i>Kabuli</i> chickpea at Full + N	0.56	NA	0.11	5.58	9.92	1.49	17.64
Narrow-leafed lupin at Full + N	1.04	0.30	1.42	7.07	18.99	0.74	29.43
Means of Full + N	0.80	NA	0.76	6.33	14.45	1.11	23.54
Designed contrast (Full + N vs. Full)	ns	*	ns	ns	**	ns	*
CV %	26.3	45.5	69.1	22	13	33.7	15.2
Significant interactions							
I x S	ns	NA	ns	ns	*	ns	ns
I _L x S	ns	NA	ns	ns	*	ns	ns
I _Q x S	ns	NA	ns	ns	ns	ns	ns
(Full + N vs. Full) x S	ns	NA	ns	ns	ns	ns	ns

¹ First pod set stages were 58 and 78 days after sowing for *Kabuli* chickpea and narrow-leafed lupin, respectively. ^a data for lupin only, ns = non-significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001 and NA = data not available for comparison. Shed leaf data were cumulative totals.

Table 6.7. Effect of irrigation level and N fertilizer application on nitrogen content (g m⁻²) at physiological maturity¹ of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	Roots	Nodules ^a	Shed leaves	Stems and branches	Leaves	Pod walls	Seeds	Total N
Nil	0.97	0.08	1.42	1.62	1.19	0.50	5.88	11.63
Half	1.35	0.43	2.14	2.00	0.95	0.98	10.41	18.05
Full	2.15	0.85	2.74	4.69	2.14	1.71	17.99	31.83
Double	2.19	0.69	3.44	3.78	1.49	1.09	9.92	22.26
S.E.M	0.16	0.04	0.46	0.79	0.22	0.23	1.44	3.02
Significance	***	**	*	*	***	**	***	**
Significant trends								
Linear (I _L)	***	***	*	ns	ns	*	*	*
Quadratic (I _Q)	*	**	ns	ns	ns	**	***	**
Species (S)								
<i>Kabuli</i> chickpea	0.87	NA	0.79	2.85	2.60	1.23	7.99	17.50
Narrow-leaved lupin	2.79	0.53	4.72	4.47	1.16	1.24	17.07	31.99
S.E.M	0.12	NA	0.28	0.18	0.11	0.20	0.95	0.95
Significance	***	NA	***	***	***	ns	***	***
Nitrogen fertilizer								
<i>Kabuli</i> chickpea at Full + N	1.34	NA	1.36	5.64	5.45	2.13	11.75	33.51
Narrow-leaved lupin at Full + N	3.63	0.59	6.73	6.83	1.82	1.68	25.14	46.40
Means of Full + N	2.49	NA	4.04	6.24	3.63	1.90	18.44	39.96
Designed contrast (Full + N vs. Full)	ns	*	ns	ns	***	ns	ns	ns
CV %	24.9	43.7	39.1	18.9	23.7	43.5	29.2	14.9
Significant interactions								
I x S	**	NA	ns	**	**	ns	**	***
I _L x S	***	NA	*	***	ns	ns	**	***
I _Q x S	ns	NA	ns	ns	ns	ns	*	**
(Full + N vs. Full) x S	ns	NA	ns	*	***	ns	*	**

¹ Physiological maturity stages were 94 days after sowing (DAS) for unirrigated *Kabuli* chickpea, 111 DAS for *Kabuli* chickpea with half, full, double irrigation and full irrigation with N, 113 DAS for unirrigated and half irrigated narrow-leaved lupin and 130 DAS for narrow-leaved lupin with full, double irrigation and full irrigation with N. ^a data for lupin only, ns = non-significant, * = P < 0.05, ** = P < 0.01, *** = P < 0.001 and NA = data not available for comparison. Shed leaf data were accumulative totals.

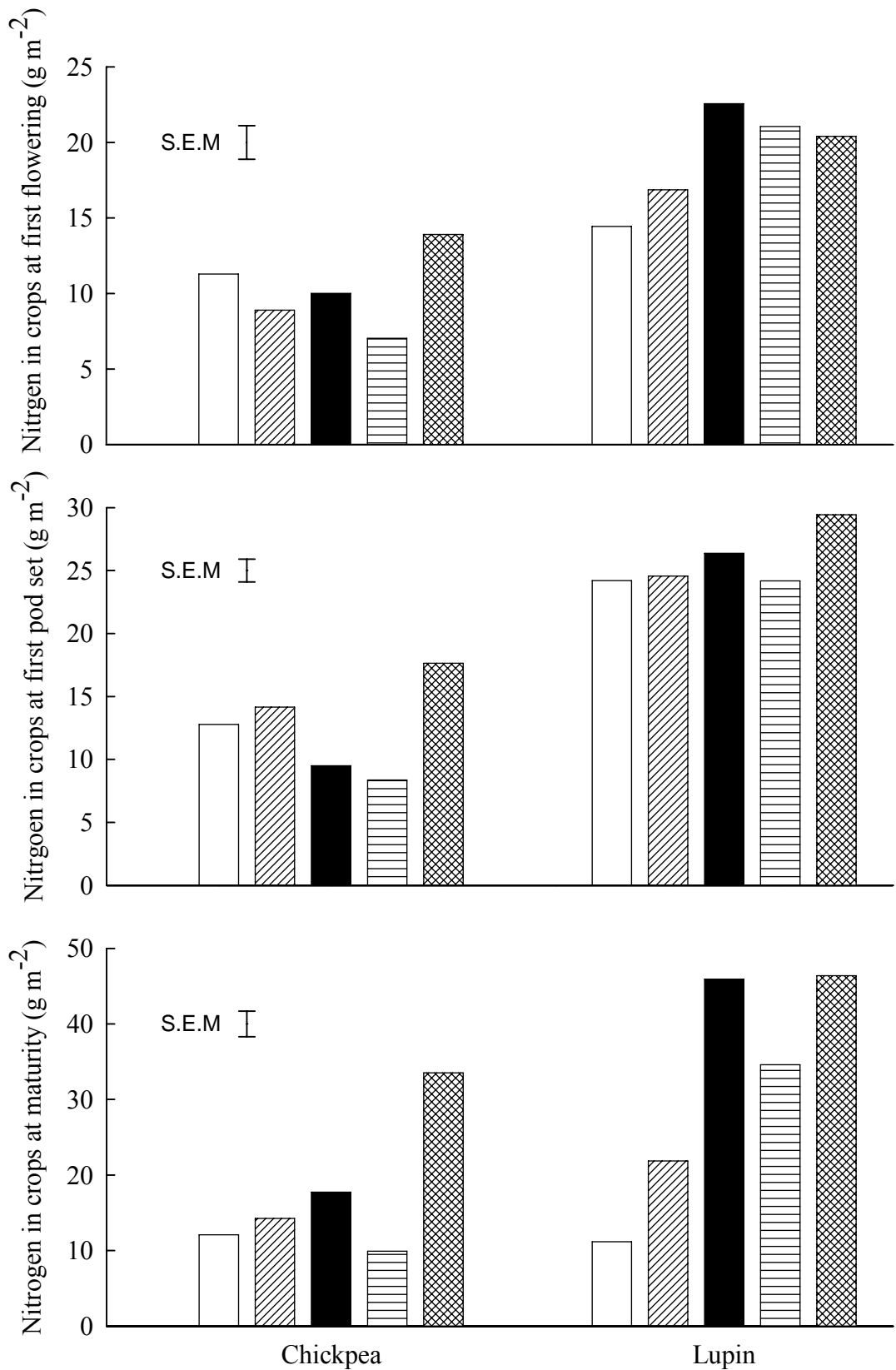


Figure 6.3. The interaction between species and irrigation level on total nitrogen accumulated at key growth stages of *Kabuli* chickpea and narrow-leaved lupin grown under different irrigation levels; nil (□), half (▨), full (■), double (▤), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean.

While stem N of *Kabuli* chickpea did not vary with irrigation in narrow-leafed lupin stem N was significantly increased by full irrigation (Table 6.7). With full irrigation, stem N was 3.0 and 6.3 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin respectively. Fertilizer N at sowing did not increase stem N at physiological maturity of narrow-leafed lupin but increased it in *Kabuli* chickpea to 5.6 g m⁻² (Figure 6.4).

Nitrogen accumulated in shed leaves differed significantly between the two legumes (Table 6.7). Until first flower there was a virtually no shed leaves in *Kabuli* chickpea (Figure 6.4). Averaged over irrigation level, cumulative shed leaf N at maturity was 0.79 and 4.72 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin. This was 5 % and 15 % of total accumulated N respectively (Table 6.7).

Nodules contributed least to total N (Figure 6.5). *Kabuli* chickpea failed to nodulate but narrow-leafed lupin nodulated. Nodule N content was relatively stable across key development stages. Averaged over irrigation level it was 0.5 g m⁻². The contribution to the total N was 2 % at physiological maturity (Table 6.7). There was an interaction between irrigation and species on root N. Irrigation only affected root N of the narrow-leafed lupin (Table 6.7). Full irrigation gave the highest root N, at 1.07 and 3.23 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin. Root N content was not affected by N fertilizer (Table 6.7). Full irrigation had the highest root N, 1.07 and 3.23 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin. The amount of N in roots was not affected by N fertilizer (Table 6.7). Averaged across irrigation levels, root N contributed 8 % and 11 % of total N in *Kabuli* chickpea and narrow-leafed lupin at physiological maturity.

Pod wall N varied significantly among irrigation levels (Table 6.7). There was a threefold increase in pod wall N with full irrigation for the two legumes. Fully-irrigated *Kabuli* chickpea and narrow-leafed lupin had pod wall N of 1.6 and 1.7 g m⁻². Water logging did not significantly reduce pod wall N. The designed contrast showed that N fertilizer did not increase pod wall N. There was no significant difference in pod wall N between *Kabuli* chickpea and narrow-leafed lupin (Table 6.7).

Seed N was significantly affected by legume species, irrigation level and the interaction between irrigation level and legume species (Table 6.7). Averaged across irrigation level, seed N in narrow-leafed lupin (17.07 g m⁻²) was significantly higher than in *Kabuli* chickpea (7.99 g m⁻²). Averaged over the two legumes, no irrigation had the lowest seed N, 5.88 g m⁻², which was about a third the amount with full irrigation. In each legume, seed N in *Kabuli* chickpea was relatively stable across irrigation level; however,

seed N of narrow-leaved lupin was significantly reduced, by 83 % with no irrigation compared with full irrigation (Figure 6.6). Added N fertilizer at sowing 150 kg N ha⁻¹ did not affect seed N of either species.

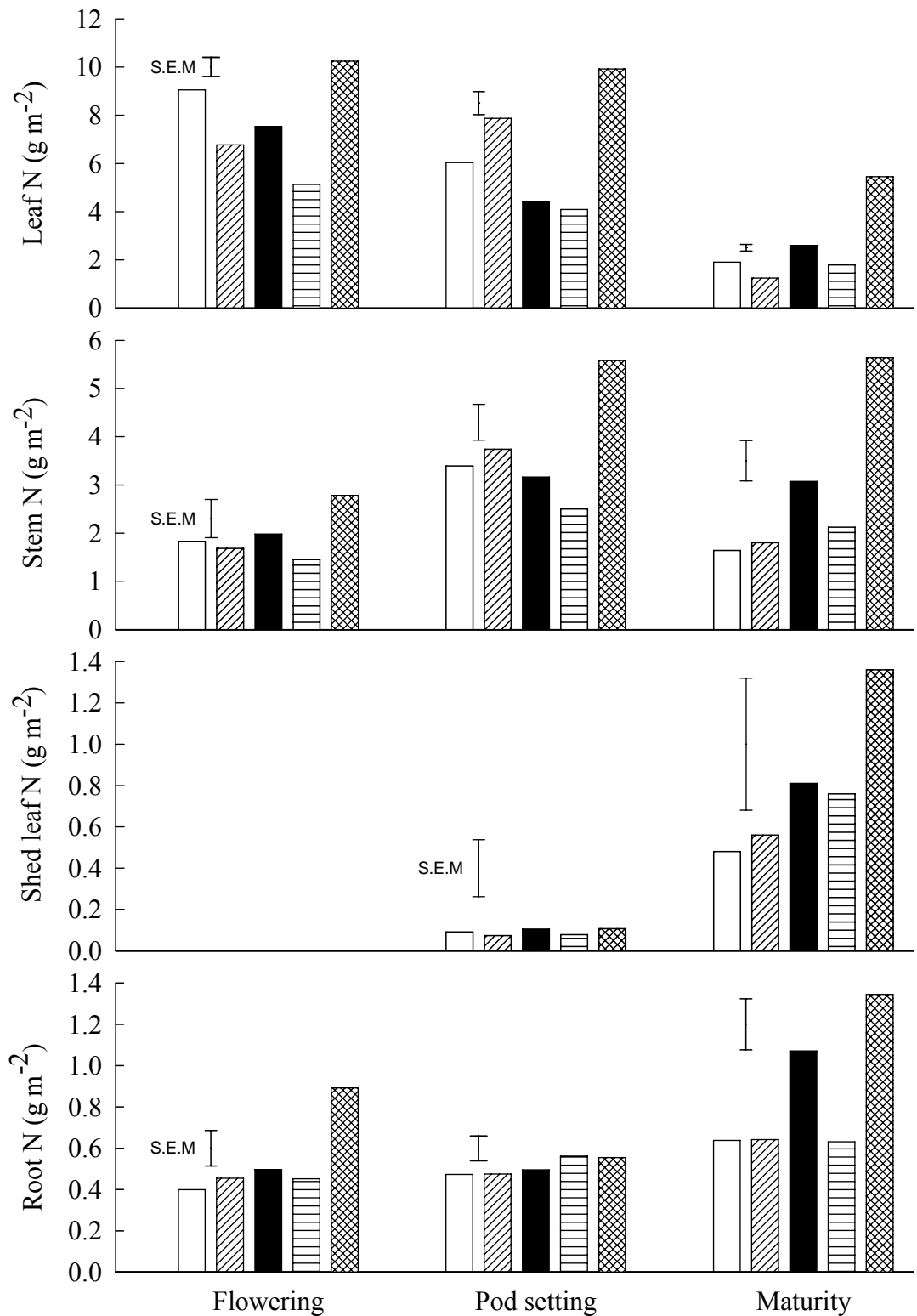


Figure 6.4. Nitrogen partitioning, at key growth stages, of *Kabuli* chickpea grown at different irrigation levels; nil (□), half (▨), full (■), double (▤), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean. Shed leaf data were cumulative totals

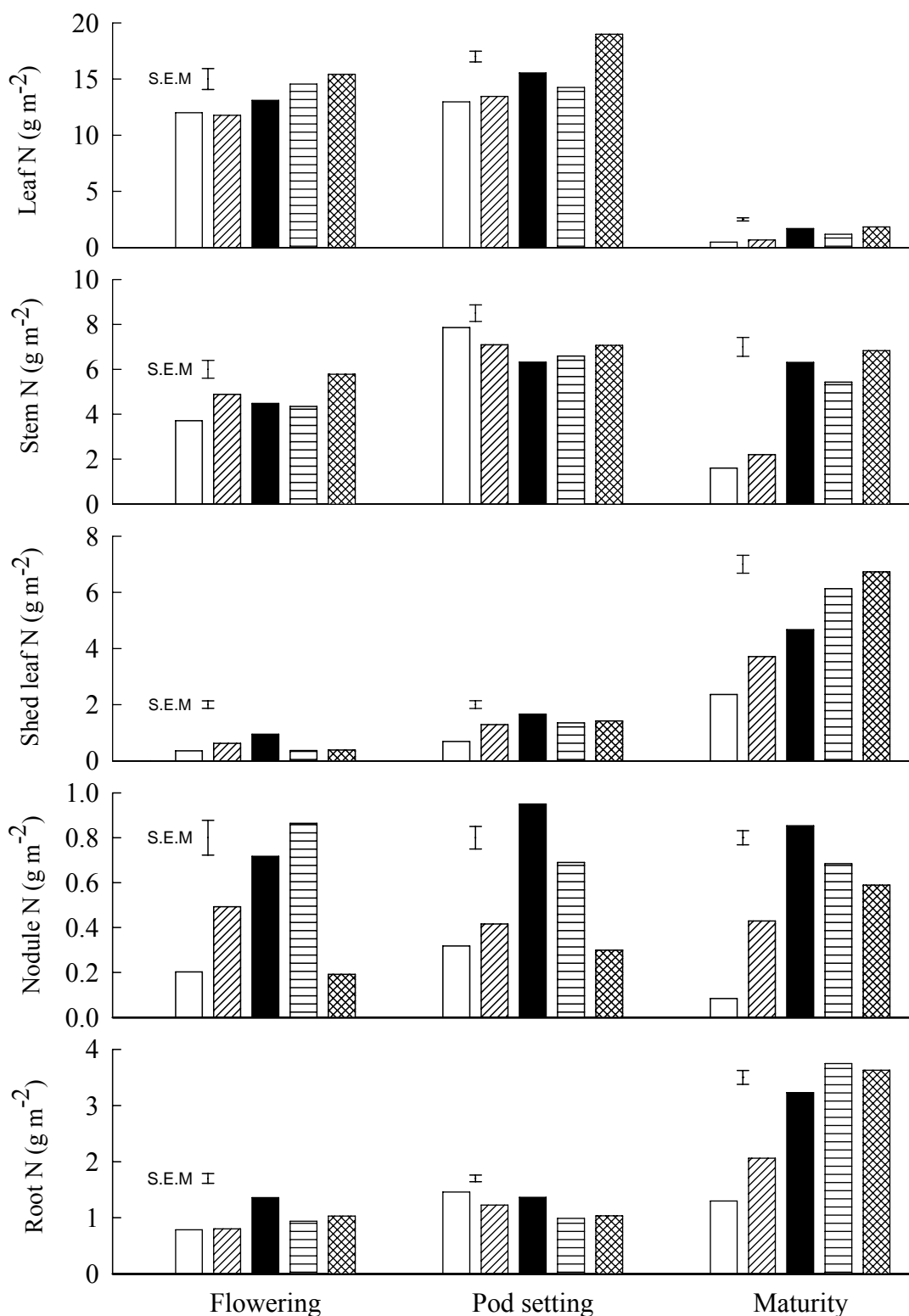


Figure 6.5. Nitrogen partitioning, at key growth stages, of narrow-leaved lupin grown at different irrigation levels; nil (\square), half (▨), full (\blacksquare), double (▤), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of the mean. Shed leaf data were cumulative totals.

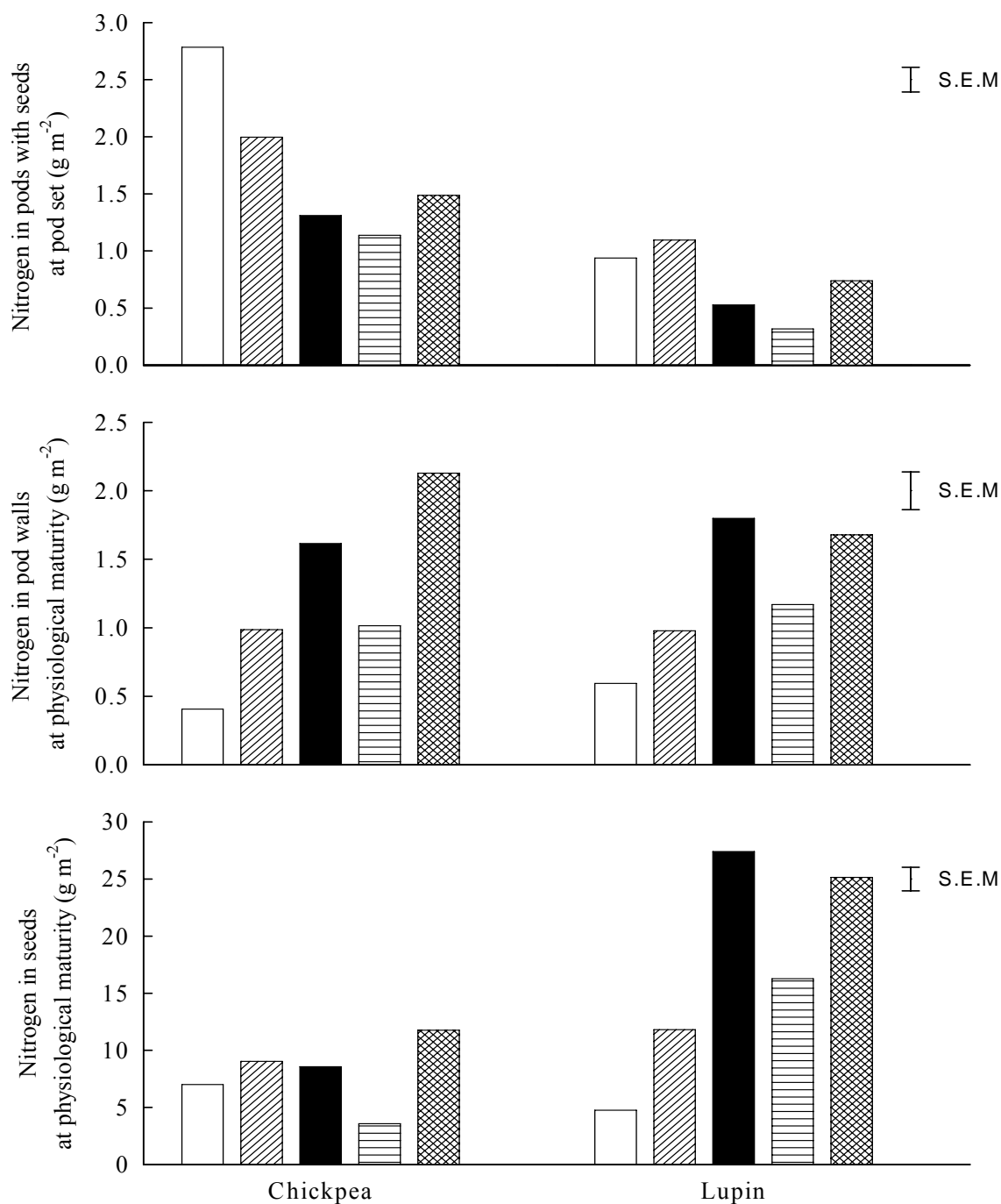


Figure 6.6. Nitrogen accumulation in pods with seeds at pod set and in pod walls and seeds at physiological maturity of *Kabuli* chickpea and narrow-leaved lupin grown at different irrigation levels; nil (□), half (▨), full (■), double (▩), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of mean. First pod set stages were 58 and 78 days after sowing for *Kabuli* chickpea and narrow-leaved lupin, respectively. Physiological maturity stages were 94 days after sowing (DAS) for unirrigated *Kabuli* chickpea, 111 DAS for *Kabuli* chickpea with half, full, double irrigation and full irrigation with N, 113 DAS for unirrigated and half irrigated narrow-leaved lupin and 130 DAS for narrow-leaved lupin with full, double irrigation and full irrigation with N.

Nitrogen accumulation efficiency

The N accumulation efficiency (NAE) was determined as the ratio between net N and net biomass at final harvest. In this study, three different values of NAE are estimated, (1) based on above-ground N, (2) above-ground N including N in shed leaves, and (3) above-ground N including N in shed leaves and roots and nodules. Table 6.8 shows that NAE was significantly affected by irrigation level and the interaction between irrigation level and legume species. Unirrigated plants had the highest efficiency at $0.017 \text{ g N g}^{-1} \text{ DM}$ and double irrigation the lowest, $0.013 \text{ g N g}^{-1} \text{ DM}$. There was a contrasting trend in NAE between *Kabuli* chickpea and narrow-leafed lupin. While NAE of the former increased with no irrigation the NAE of the latter was increased with full irrigation. The NAE of narrow-leafed lupin was not significantly increased by N fertilizer but the NAE of *Kabuli* chickpea increased markedly (Figure 6.7).

Although the overall means of NAE, calculated from the three methods, did not show a marked difference, a difference in NAE between the two legumes was only indicated by the NAE based on above-ground TDM including shed leaves and the above-ground TDM including shed leaves, roots and nodules. For the last two methods the average NAE of narrow-leafed lupin at $0.016 \text{ g N g}^{-1} \text{ DM}$ was significantly higher than in *Kabuli* chickpea at $0.015 \text{ g N g}^{-1} \text{ DM}$ (Table 6.8).

Nitrogen harvest index

The NHI was determined as the ratio between the total amount of seed N and total N. Total N was estimated from above-ground N, above-ground N including the N in shed leaves and above-ground N including N in shed leaves and N in roots and nodules. The NHI was not affected by either irrigation level or N fertilizer (Table 6.8). The two legumes differed significantly in their NHI only when the NHI was based on above-ground N only at crop maturity, in *Kabuli* chickpea the NHI was 0.55 and in narrow-leafed lupin it was 0.70 (Figure 6.8). When the NHI was based on above-ground biomass including shed leaves, roots and nodule the NHIs of *Kabuli* chickpea and narrow-leafed lupin were 0.50 and 0.51, respectively (Table 6.8).

Table 6.8. Effect of irrigation level and N fertilizer application on nitrogen harvest index (NHI) and N accumulation efficiency (NAE, g N g⁻¹DM) of *Kabuli* chickpea and narrow-leaved lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

Irrigation level (I)	NHI			NAE (g N g ⁻¹ DM)		
	¹ N	² N with SL	³ N with SL, roots and nodules	¹ N	² N with SL	³ N with SL, roots and nodules
Nil	0.62	0.53	0.48	0.017	0.018	0.017
Half	0.72	0.64	0.59	0.015	0.016	0.015
Full	0.64	0.59	0.54	0.015	0.015	0.015
Double	0.54	0.46	0.41	0.013	0.013	0.013
S.E.M	0.04	0.04	0.04	0.001	0.001	0.001
Significance	ns	ns	ns	*	**	*
Significant trends						
Linear (I _L)	ns	ns	ns	**	***	**
Quadratic (I _Q)	ns	*	*	ns	ns	ns
Species (S)						
<i>Kabuli</i> chickpea	0.55	0.52	0.50	0.015	0.015	0.015
Narrow-leaved lupin	0.70	0.57	0.51	0.015	0.016	0.016
S.E.M	0.02	0.02	0.02	0.001	0.0004	0.0004
Significance	***	ns	ns	ns	*	*
Nitrogen fertilizer						
<i>Kabuli</i> chickpea at Full + N	0.47	0.45	0.44	0.016	0.017	0.017
Narrow-leaved lupin at Full + N	0.71	0.59	0.53	0.017	0.017	0.017
Means of Full + N	0.59	0.52	0.49	0.017	0.017	0.017
Designed contrast (Full + N vs. Full)	ns	ns	ns	ns	*	ns
CV %	10.7	15.0	16.3	13.5	9.5	9.7
Significant interactions						
I x S	*	*	*	**	*	***
I _L x S	**	**	**	***	***	***
I _Q x S	ns	ns	ns	*	ns	*
(Full + N vs. Full) x S	ns	ns	ns	*	ns	ns

¹ above-ground N only; ² above-ground N including N in shed leaves (SL); ³ above-ground N including N in shed leaves and in roots and nodules; ns = non-significant; * = P < 0.05; ** = P < 0.01 and *** = P < 0.001.

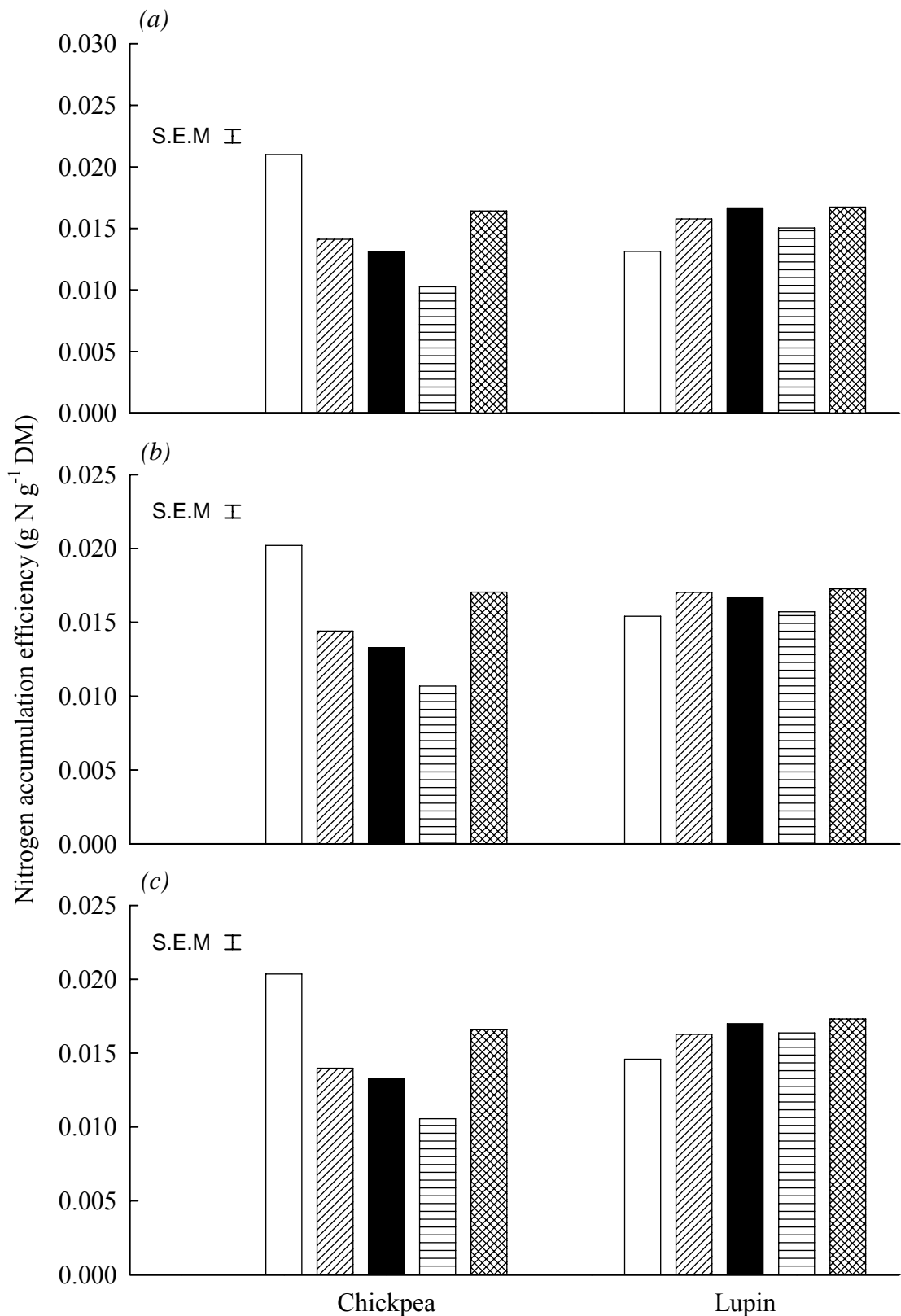


Figure 6.7. Nitrogen accumulation efficiency; (a), based on above-ground N only, (b), above-ground N including N in shed leaves, and (c), above-ground N including N in shed leaves and roots and nodules of *Kabuli* chickpea and narrow-leaved lupin grown at different irrigation levels; nil (□), half (▨), full (■), double (▩), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of the mean.

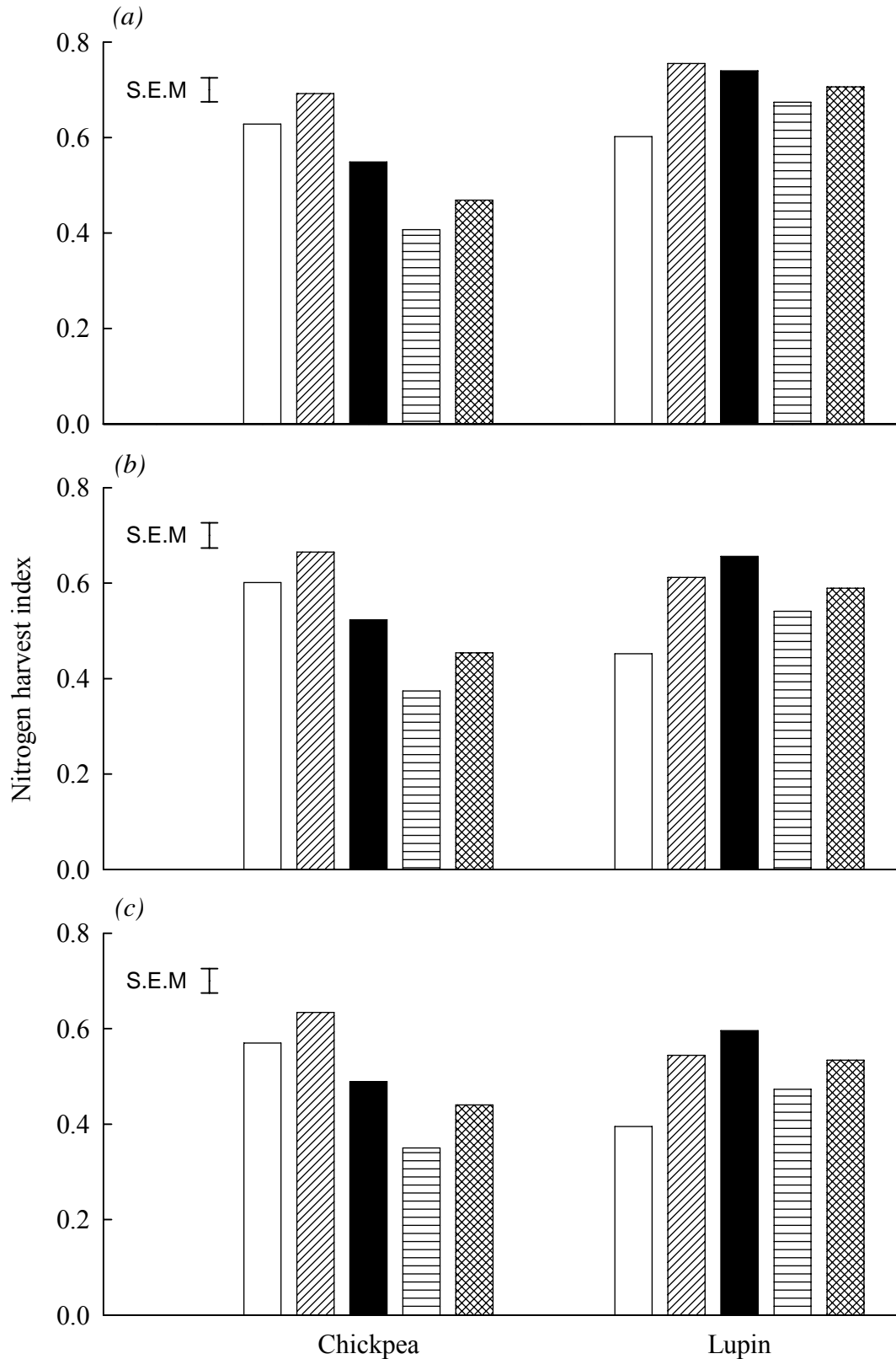


Figure 6.8. Nitrogen harvest index; (a), based on above-ground N only, (b), above-ground N including N in shed leaves, and (c), above-ground N including N in shed leaves and roots and nodules *Kabuli* chickpea and narrow-leaved lupin grown at different irrigation levels; nil (\square), half (▨), full (\blacksquare), double (▩), and full + N (▩) at Lincoln University, Canterbury, New Zealand in 2007/08. S.E.M = standard error of the mean.

Relationship between total dry matter and seed yield and plant nitrogen content

In this study, the total amount of DM and N were determined from (1) only above-ground plant parts at maturity, (2) above-ground plant parts including shed leaves and (3) above-ground plant parts including shed leaves and roots and nodules. The total seed N was also positively related to total N estimated from the three methods (Table 6.9). The *r* values of the N relationship were higher than those for biomass (Table 6.10). Only in the narrow-leafed lupin were crop HI and NHI significantly related to seed yield. Nitrogen accumulation efficiency (NAE) was not related to other parameters in *Kabuli* chickpea. However, in narrow-leafed lupin, NAE was significantly related to HI and NHI (Table 6.10). There was a linear relationship between net N accumulation and net biomass accumulation at physiological maturity in each species (Figure 6.9, 6.10 and 6.11). The *R*² values for the relationships were higher in narrow-leafed lupin than in *Kabuli* chickpea.

Table 6.9. Correlation matrices between nitrogen parameters and total dry matter (TDM), seed yield and crop harvest index (CHI) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

	TDM ¹	TDM ²	TDM ³	Seed yield	CHI ¹	CHI ²	CHI ³
<i>Kabuli</i> chickpea							
Total N ¹	0.86**	0.85**	0.85**	0.61*	-0.19	-0.15	-0.13
Total N ²	0.84**	0.84**	0.83**	0.59*	-0.17	-0.14	-0.12
Total N ³	0.87**	0.86**	0.86**	0.57*	-0.23	-0.20	-0.18
Seed N	0.68**	0.66**	0.65**	0.87**	0.28	0.32	0.34
NHI ¹	-0.26	-0.28	-0.28	0.48	0.95**	0.95**	0.95**
NHI ²	-0.25	-0.26	-0.27	0.49	0.96**	0.96**	0.96**
NHI ³	-0.23	-0.25	-0.26	0.50	0.96**	0.96**	0.96**
NAE ¹	-0.28	-0.29	-0.29	-0.11	0.39	0.37	0.37
NAE ²	-0.16	-0.17	-0.18	-0.02	0.36	0.35	0.35
NAE ³	-0.23	-0.24	-0.25	-0.10	0.35	0.34	0.34
Narrow-leafed lupin							
Total N ¹	0.98**	0.98**	0.97**	0.99**	0.52*	0.64*	0.67**
Total N ²	0.98**	0.98**	0.98**	0.97**	0.49	0.59*	0.62*
Total N ³	0.98**	0.98**	0.99**	0.97**	0.48	0.58*	0.61*
Seed N	0.98**	0.97**	0.97**	0.99**	0.57*	0.68*	0.71**
NHI ¹	0.42	0.42	0.42	0.52*	0.90**	0.87**	0.86**
NHI ²	0.57*	0.55*	0.55*	0.68**	0.91**	0.95**	0.96**
NHI ³	0.59*	0.56*	0.56*	0.70**	0.89**	0.94**	0.95**
NAE ¹	0.39	0.39	0.40	0.51	0.90**	0.87**	0.86**
NAE ²	0.09	0.10	0.11	0.22	0.82**	0.74**	0.72**
NAE ³	0.38	0.40	0.41	0.47	0.81**	0.76**	0.74**

* = *P* < 0.05 and ** = *P* < 0.01. Where no significance is indicated values are not significant (*P* > 0.05). NHI = nitrogen harvest index, NAE = nitrogen accumulation efficiency. Superscripts; ¹, ², and ³ = values were determined based on total above-ground plant parts only, total above-ground plant parts with shed leaves and total above-ground plant parts with shed leaves and roots and nodules; respectively.

Table 6.10. Correlation matrices between nitrogen parameters and above-ground yield (including shed leaves) of *Kabuli* chickpea and narrow-leafed lupin grown at Lincoln University, Canterbury, New Zealand in 2007/08.

	Seed yield	TDM	Seed N	Total N	HI	NHI
<i>Kabuli</i> chickpea						
TDM	0.69**					
Seed N	0.87**	0.66**				
Total N	0.59*	0.84**	0.81**			
HI	0.36	-0.40	0.32	-0.14		
NHI	0.49	-0.26	0.50	-0.05	0.96**	
NAE	-0.02	-0.17	0.43	0.38	0.35	0.35
Narrow-leafed lupin						
TDM	0.97**					
Seed N	0.99**	0.97**				
Total N	0.97**	0.98**	0.98**			
HI	0.68**	0.52*	0.68**	0.59*		
NHI	0.68**	0.55*	0.68**	0.57*	0.95**	
NAE	0.22	0.10	0.25	0.24	0.74**	0.61**

* = $P < 0.05$ and ** = $P < 0.01$. Where no significance is indicated values are not significant ($P > 0.05$). TDM = total above-ground dry matter including shed leaves, HI = harvest index, NHI = nitrogen harvest index, NAE = nitrogen accumulation efficiency.

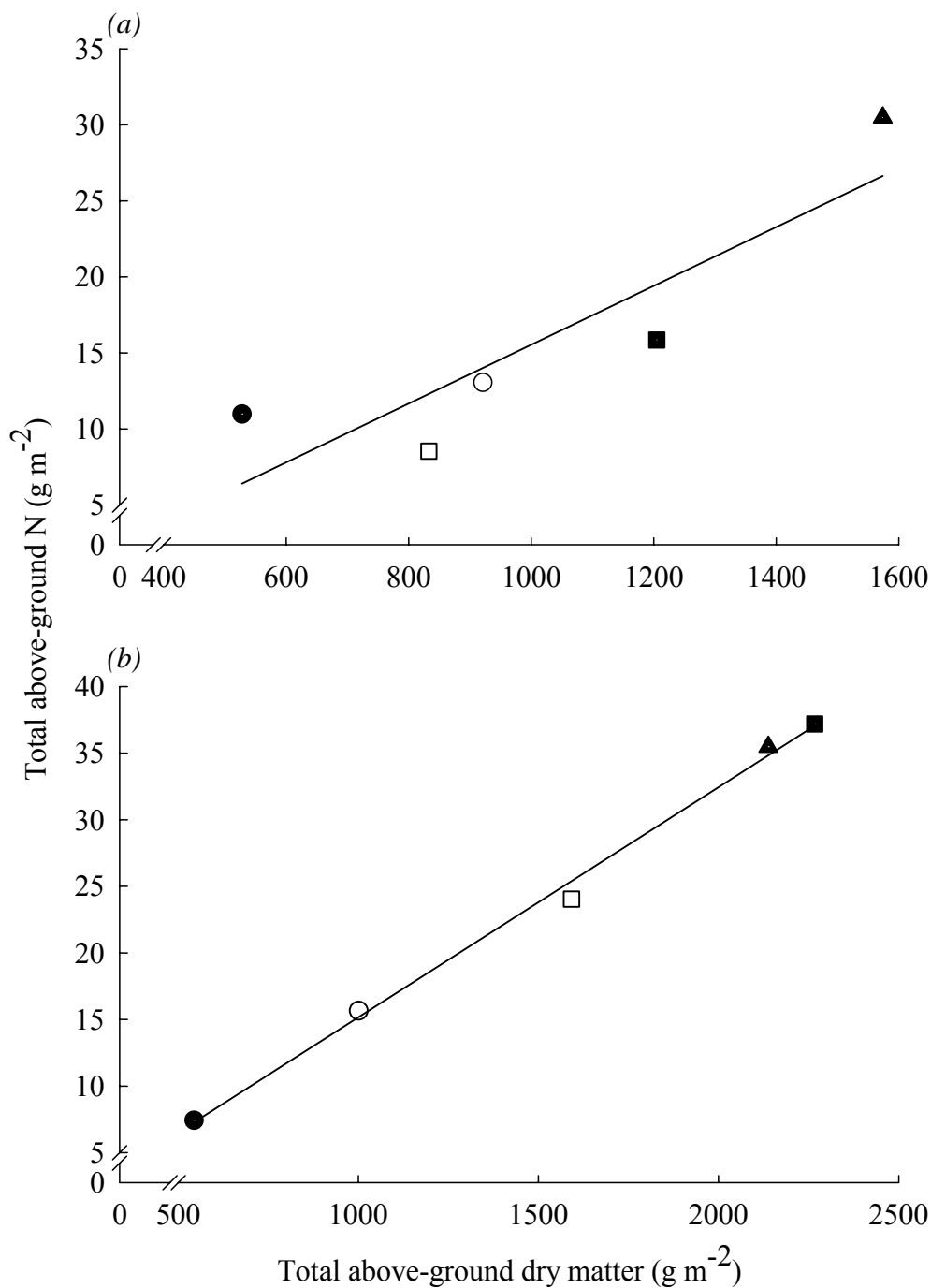


Figure 6.9. Relationship between total above-ground nitrogen and total dry matter at physiological maturity (excluding shed leaves) in *Kabuli* chickpea (a), $Y = -3.81 + 0.02X$ ($R^2 = 0.79$) and narrow-leaved lupin (b), $Y = -2.12 + 0.02X$ ($R^2 = 0.99$), grown at different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08

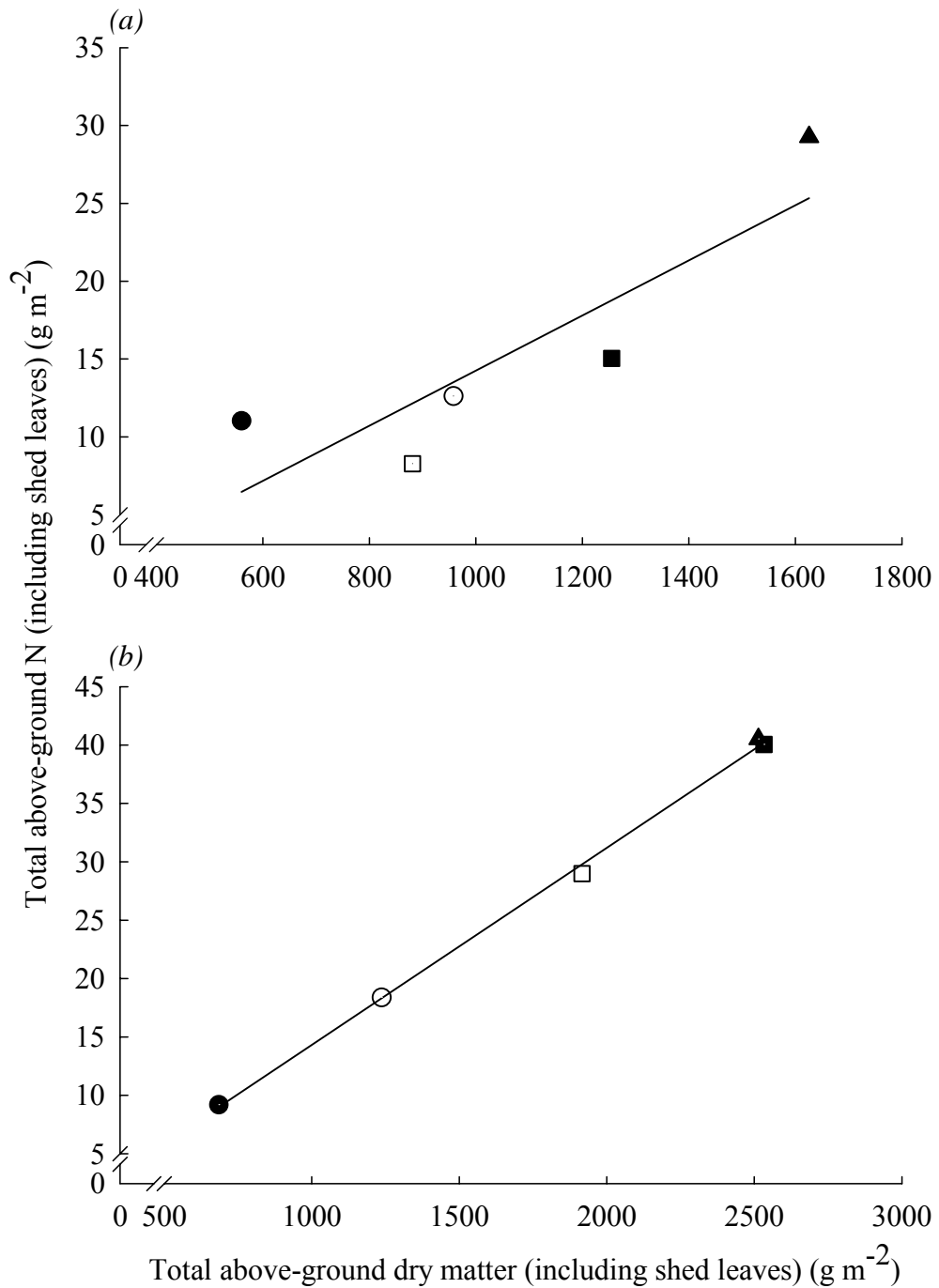


Figure 6.10. Relationship between total above-ground nitrogen and total dry matter at physiological maturity (including shed leaves) in *Kabuli* chickpea (a), $Y = -3.44 + 0.02X$ ($R^2 = 0.76$) and narrow-leaved lupin (b), $Y = -2.58 + 0.02X$ ($R^2 = 0.99$), grown at different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08.

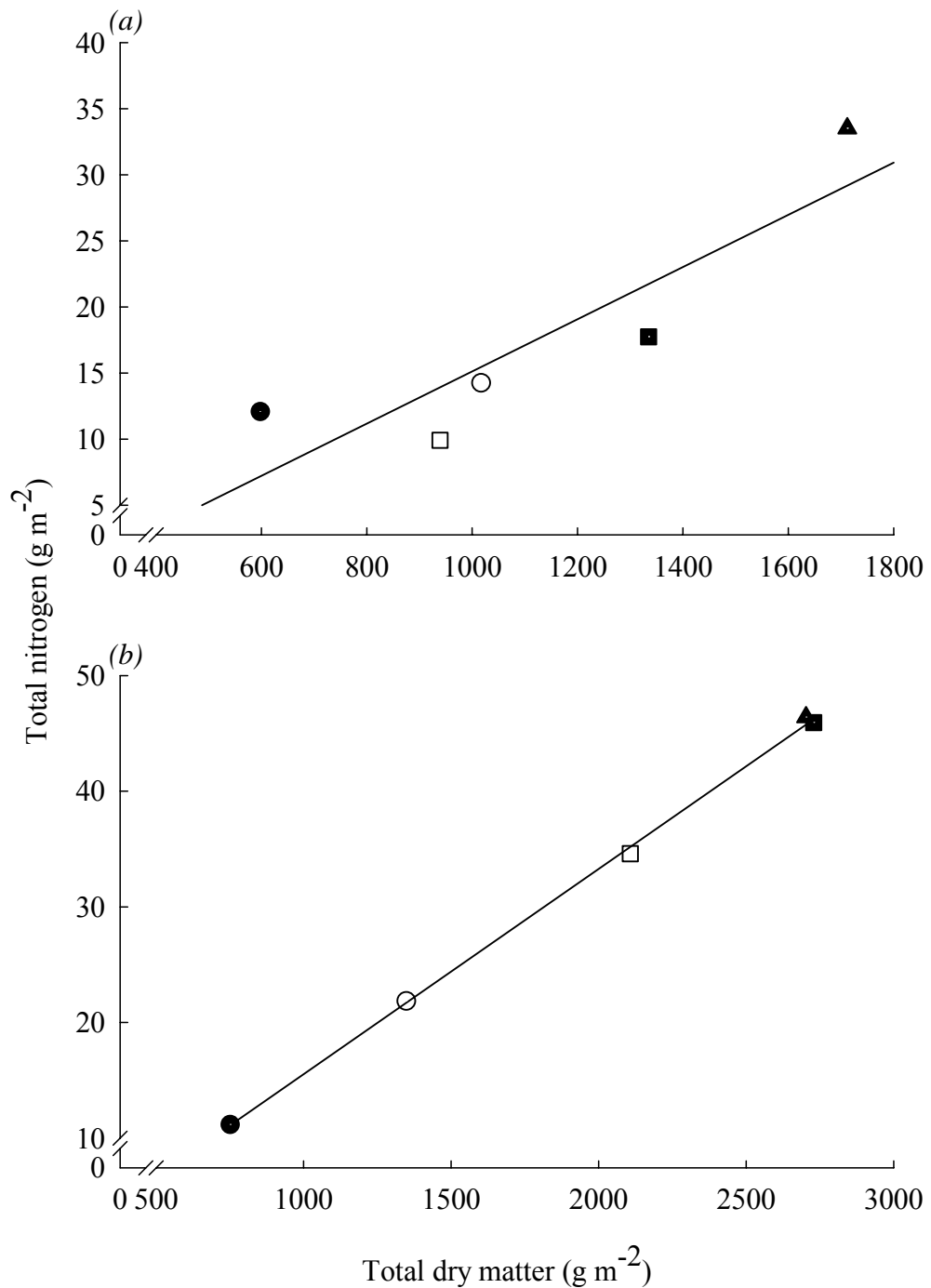


Figure 6.11. Relationship between total nitrogen accumulation and total dry matter at physiological maturity (including roots, nodules and shed leaves) in *Kabuli* chickpea (a), $Y = -4.62 + 0.02X$ ($R^2 = 0.78$) and narrow-leafed lupin (b), $Y = -2.23 + 0.02X$ ($R^2 = 0.99$), grown at different irrigation levels; nil (●), half (○), full (■), double (□) and full + N (▲) at Lincoln University, Canterbury, New Zealand in 2007/08.

Discussion

Nitrogen concentration

Generally both *Kabuli* chickpea and narrow-leafed lupin showed a reduction in leaf and stem N concentration at physiological maturity (Figure 6.1 and 6.2). This decrease in N concentration at physiological maturity was reported in soybean, pigeon pea (*Cajanus cajan* L.), and peanut. (De Vries *et al.*, 1989), in narrow-leafed lupin (Farrington *et al.*, 1977; Unkovich *et al.*, 1994) and in chickpea (Soltani *et al.*, 2006). The reduction in N concentration suggests remobilization from leaves and stems to seeds and it is hypothesized as “self-destruction” since it can accelerate leaf senescence (Sinclair and de Wit, 1976).

In *Kabuli* chickpea, the leaf N concentration fell from 4.6 % at first flower to 1.7 % at physiological maturity (Figure 6.1). The N concentration of *Kabuli* chickpea leaves at first flower was in the range reported by Soltani *et al.* (2006). However, the leaf N concentration of *Kabuli* chickpea at physiological maturity was lower than those reported by Evans (1982) and Soltani *et al.* (2006). This might be because the *Kabuli* chickpea in this study failed to nodulate and remobilization from leaves to seed caused a greater reduction in leaf N concentration at physiological maturity.

At physiological maturity, there was a marked reduction in the leaf N concentration in *Kabuli* chickpea with half irrigation. Nitrogen might be remobilized from leaf for seed growth since Foster *et al.* (1995) found that under mild drought stress, a large amount of seed N was derived from remobilization. However, they also suggested that under more severe stress remobilization was decreased. In this study, the leaf N concentration in unirrigated *Kabuli* chickpea was higher than with half irrigation. Hence, if the suggestion of Foster *et al.* (1995) is true, remobilization of N in *Kabuli* chickpea might be reduced by severe water stress with no irrigation. An alternative explanation is that since the nil irrigation treatment reduced seed and pod number, as discussed in Chapter 4, this might lead to low N seed demand and low N translocation from leaves (De Vries *et al.*, 1989). The stem N concentration of *Kabuli* chickpea showed similar responses to leaves. This response was also reported by De Vries *et al.* (1989).

In this study, the leaf N concentration of narrow-leafed lupin decreased from 3.5 % at first flower to 1.4 % at physiological maturity. The values are similar to those of Farrington *et al.* (1977) and Unkovich *et al.* (1994). Duthion and Pigeaire (1993) reported

that N concentration in white lupin (*Lupinus albus* L.) between anthesis and seed filling was relatively stable. This might also be typical of leaf N concentration in narrow-leaved lupin in this study. There was no marked change in leaf N concentration between first flower and pod set in narrow-leaved lupin (Figure 6.2).

The stem N concentration of narrow-leaved lupin fell to 0.6 % at maturity. This value is similar to that reported by Howieson *et al.* (1998), of 0.7 %. Howieson *et al.* (1998) suggested the marked decrease in the N concentration of vegetative parts of narrow-leaved lupin, at maturity, indicates the efficiency of N remobilization to seed.

The root N concentration of *Kabuli* chickpea at physiological maturity was not affected by irrigation or by N fertilizer application (Table 6.3). On average, root N concentration was 1.36 %. This is similar to values reported by Evans (1982). Also, the tendency of a higher N concentration at physiological maturity compared to first flower also agrees with Evans (1982). Interestingly, there was a drop in root N concentration at first pod set (58 DAS) at all irrigation levels (Figure 6.1). This behaviour was also reported in common beans by Foster *et al.* (1995). The reduction in root N concentration at this stage might be due to remobilization to support high N demand for both vegetative and reproductive growth. However, there are no results in the literature to confirm this. Surprisingly, the root N concentration in narrow-leaved lupin (all treatments) and *Kabuli* chickpea in no irrigation, full and full + N treatments at physiological maturity was higher than at first flowering. These results contradict those of Hooda *et al.* (1986) and Unkovich *et al.* (1994). However, they do support the explanation of Gladstones and Loneragan (1975). As there might be sufficient N in tops for seed development and as stems mature, excess N in stems can move down to roots and soil.

The mean N concentration in shed leaves was 1.7 %. This result is similar to that of Unkovich *et al.* (1994) who indicated that the N concentration of shed narrow-leaved lupin leaves was around 2 %. Ayaz (2001) reported an N concentration in shed chickpea leaves of 1.83 to 2.03 % and for narrow leaved lupin of 0.75 to 1.60 %. Soltani *et al.* (2006) also reported that N concentration in senescent chickpea leaf was 1.48 to 2.02 %. The N concentration of shed leaves was not affected by irrigation, N fertilizer or legume species (Table 6.3). It was also not affected by plant population and sowing depth (Ayaz, 2001). The N concentration value in shed leaves, senescent leaves and stems at maturity might be important for quantifying the amount of N which can be mineralized after crop residue incorporation as N availability after decomposition depends strongly on the C:N ratio of crop residues (Cameron, 1992).

The average seed N concentration of *Kabuli* chickpea was 3.05 % and it was 4.8 % in narrow-leafed lupin (Table 6.3). These values are very similar to those for chickpea reported by Hooda *et al.* (1986) and Soltani *et al.* (2006) and for narrow-leafed lupin reported by Howieson *et al.* (1998) and Ayaz (2001). The seed N concentration in narrow-leafed lupin was not affected by either irrigation level or by additional N fertilizer. The less variable seed N concentration in narrow-leafed lupin supports the result of Muchow *et al.* (1993) who reported that seed N concentration of soybean (*Glycine max* L.), mungbean (*Vigna radiata* L.) and cowpea (*Vigna unguiculata* L. Walp.) was stable across growing conditions. In contrast, the seed N concentration of the *Kabuli* chickpea was significantly increased by no irrigation and the addition of N fertilizer at sowing. This agrees with Chapman and Muchow (1985) who reported that the N concentration of soybean seed was increased under water limiting condition. McConnell *et al.* (2002) also reported that seed N concentration was increased by additional N fertilizer at sowing if compared to uninoculated chickpea. Foliage N application at first flowering also increased seed N content of chickpea (Palta *et al.*, 2005).

Nitrogen accumulation

Nitrogen accumulation at physiological maturity of narrow-leafed lupin was strongly affected by water supply (Figure 6.3). The reduction in N accumulation was 75 % under water stress and 24 % with excess water. These results agree with those for soybean, cowpea and pigeon pea reported by Chapman and Muchow (1985); in soybean and pigeon pea by De Vries *et al.* (1989); in soybean, mungbean and cowpea by Muchow *et al.* (1993) and in mungbean by Thomas *et al.* (2004). The reduction in total crop N might be attributed to reduced N fixation as N fixation represents the majority of total N accumulation and N fixation is strongly affected by water stress (Castellanos *et al.*, 1996; Thomas *et al.*, 2004; Sinclair *et al.*, 2007).

In *Kabuli* chickpea, there was no significant effect of irrigation on total N accumulated at physiological maturity. As noted above, the crops failed to nodulate. The crop therefore must have depended entirely on N uptake from the soil. Purcell *et al.* (2004) reported, in non-nodulating soybean, there was no significant difference in N accumulation rate between droughted and well-watered plants. Bacanamwo and Purcell (1999) also indicated that in soybean dependent on nitrate supply, N accumulation was less affected by flooding stress. Hence, their results support the findings in this study.

Added N fertilizer only increased total N in *Kabuli* chickpea. The total N in *Kabuli* chickpea nearly doubled with added N fertilizer at sowing compared to full irrigation without N fertilizer (Figure 6.3). Similar results with *Kabuli* chickpea were reported by Doughton *et al.* (1993) who observed a high N content in chickpea grown on a high N soil at crop establishment. Application of foliage N, at first flower also increased *Kabuli* chickpea plant total N (Palta *et al.*, 2005). However, total N in narrow-leafed lupin, at physiological maturity, was not affected by N fertilizer. This supports the results of Evans *et al.* (1987) who showed that there was no response in lupin total N to N fertilizer application.

Under full irrigation, total above-ground N excluding shed leaves in *Kabuli* chickpea was 15.8 g m⁻² and it was 37.1 g m⁻² in narrow-leafed lupin. These results are in a range of values (10.4 to 33.3 g m⁻²) in chickpea reported by Soltani *et al.* (2006) and in lupin by Armstrong *et al.* (1997) and Howieson *et al.* (1998). Total plant N including shed leaves and roots and nodules was 17.7 and 45.9 for *Kabuli* chickpea and narrow-leafed lupin, respectively. These values were very similar to those reported by Turpin *et al.* (2002).

Nitrogen accumulation efficiency

Nitrogen accumulation efficiency (NAE) was affected by irrigation level. Chapman and Muchow (1985) reported that while the NAE of soybean (cv. Durack) declined with dry conditions, that of cowpea increased. In this study the NAE of *Kabuli* chickpea increased, regardless of methods of NAE determination with no irrigation. In narrow-leafed lupin the NAE (based on above-ground N excluding shed leaves) was reduced with no irrigation. However, the NAE of narrow-leafed lupin, based on above-ground N including N in shed leaves and roots and nodules was not affected by irrigation level. Double irrigation (water logging) only reduced the NAE (including shed leaves) of *Kabuli* chickpea (Table 6.8).

Averaged across irrigation levels the NAE of narrow-leafed lupin was significantly higher than that of *Kabuli* chickpea (Table 6.8). This supports the findings of Ayaz (2001). Chapman and Muchow (1985) also reported significant variation in the NAE of several grain legumes. In this study, the NAE (above-ground N only) of *Kabuli* chickpea and narrow-leafed lupin was 0.015. These values were lower than those reported by Ayaz (2001). The reason for the low NAE in *Kabuli* chickpea might still be the failure to nodulate and N accumulation was dependent on soil N; there might a decrease in N

assimilation. In plots with full irrigation and N fertilizer, the NAE (including shed leaves) was 0.017. For narrow-leafed lupin, the mean NAE values were low. This might be caused by the lowest NAE (including shed leaves) in the no irrigation treatment (0.015). Fully-irrigated lupin had an NAE (including shed leaves) of 0.017. This value was virtually the same as the value for mungbean reported by Bushby and Lawn (1992).

An alternative explanation for the lower NAE, compared to the results of Ayaz (2001) might be that total DM in this study was higher but N accumulation was lower than the values of Ayaz (2001) for *Kabuli* chickpea. For narrow-leafed lupin, while the total DM in this study was 55 % higher than Ayaz (2001), total accumulated N was only 22 % higher. This gave a lower NAE, ratio of accumulated N to accumulated DM, in this study.

Additional N fertilizer at sowing only increased the NAE of *Kabuli* chickpea. The reason for this might be because the N fertilizer only increased total N accumulation at physiological maturity but not the TDM compared with full irrigation as discussed in Chapter 4. In narrow-leafed lupin, N fertilizer did not increase N accumulation or TDM; hence, there was no significant difference in NAE between full irrigation with and without N fertilizer.

Nitrogen harvest index

In this work irrigation level did not affect the NHI based on above-ground N, excluding shed leaves (Table 6.8). This agrees with Thomas *et al.* (2004) who reported that the NHI of mungbean was not affected by different water regimes. However, there was a significant effect of the interaction between irrigation level and legume species on the NHI based on above-ground N including shed leaves and the NHI based on above-ground N including N in shed leaves and roots and nodules. The NHI of *Kabuli* chickpea was relatively stable but the NHI of narrow-leafed lupin was decreased with no irrigation. The results support those of Foster *et al.* (1995) who indicated a reduced NHI (based on above-ground N including shed leaves and roots) of beans, grown under water stress, in a glasshouse. Chapman and Muchow (1985) also reported that the NHI of soybean, cowpea and pigeon pea was significantly reduced under dry conditions.

Averaged across irrigation levels, the NHIs excluding shed leaves were 0.55 for *Kabuli* chickpea and 0.70 for the narrow-leafed lupin. These values are similar to those in common beans (Foster *et al.*, 1995) and in mungbean (Thomas *et al.*, 2004). Muchow *et al.* (1993) also reported the NHI of mungbean ranged from 0.34 to 0.64 and from 0.27 to 0.63 in cowpea.

The NHIs (including shed leaves) were not significantly different between *Kabuli* chickpea (0.52) and narrow-leafed lupin (0.57). Chalk (1998) and Howieson *et al.* (1998) held that the NHI can be used as an index to evaluate the N benefit of a grain legume to cropping systems. Grain legumes with a high dependency on N fixation and a low NHI tend to give N benefits to a cropping system. In this work, although the amount of N in narrow-leafed lupin seed was significantly higher than in *Kabuli* chickpea, their NHIs (including shed leaves) were not different between *Kabuli* chickpea and narrow-leafed lupin which nodulated and accumulated more total N by physiological maturity. This implies that narrow-leafed lupin should give a greater N benefit to a cropping system than *Kabuli* chickpea.

In both legumes there was a significant relationship between CHI and NHI and the two indices were also related to seed yield in narrow-leafed lupin (Table 6.10). This is in agreement with Ayaz (2001) for grain legumes, the result of Rattunde and Frey (1986) for oats (*Avena sativa* L.) and the results of Löffler and Busch (1982) for wheat (*Triticum aestivum* L.). Rattunde and Frey (1986) suggested that as the NHI and the CHI are closely related and determination of the NHI is a costly and time-consuming the CHI should be used as an alternative trait for improving both NHI and CHI.

Implication for agronomic practices

Total N accumulated and NHI were affected by irrigation. However, the NHI was less affected by irrigation. To increase the N amount in seed development, and the N content of crop residues, irrigation should aim at increasing total N accumulation. Also, as there is a close relationship between TDM and total N accumulated, and between seed N and total N (Table 6.10). Irrigation to achieve potential growth and seed yield is also important for increasing total N accumulated, in particular N from biological fixation. In this study, the direct effect of irrigation on N fixation was not determined. However, there were some indications of the effect of irrigation on N fixation; the reduction in total N in nodules in the no irrigation treatment was the result of reduced nodulation. Hence, legume crops should be fully irrigated to increase seed yield, N accumulation and N fixation. Herridge *et al.* (2001) suggested that the best way of increasing N fixation can be to give the crop optimum management to obtain a high seed yield.

As *Kabuli* chickpea failed to nodulate, it is impossible to determine the effect of N fertilizer on N fixation. However, in narrow-leafed lupin, N fertilizer did not increase total N or seed N content by physiological maturity. The application of N fertilizer only

substitutes for the amount of N fixed (Evans *et al.*, 1987). Hence, N fertilizer application might not be of economic importance for narrow-leafed lupin.

Conclusions

1. At first flower, leaf N concentration was not affected by irrigation. Leaf N concentrations were 4.6 and 3.4 % for *Kabuli* chickpea and narrow-leafed lupin, respectively. Nitrogen fertilizer only increased the leaf N concentration of *Kabuli* chickpea (5.4 %).
2. At physiological maturity, narrow-leafed lupin leaf N concentration was not affected by irrigation or by N fertilizer. However, leaf N concentration of *Kabuli* chickpea was decreased with half irrigation to 1.2 % and increased to 2.4 % with full irrigation and N fertilizer.
3. Irrigation level and N fertilizer did not affect the seed N concentration of narrow-leafed lupin; the average N concentration was 4.8 %. However, seed N concentration of *Kabuli* chickpea was increased from 2.6 % with full irrigation to 3.9 and 3.6 % in no irrigation and in full irrigation with N fertilizer, respectively.
4. Total N accumulation (based on above-ground N including N in shed leaves and roots and nodules) of *Kabuli* chickpea was not affected by irrigation level. At full irrigation, total N in *Kabuli* chickpea was 17.7 g m⁻². In contrast, N accumulated in narrow-leafed lupin was strongly affected by irrigation. Fully-irrigated narrow-leafed lupin produced 45.9 g N m⁻². This was reduced by 75 % with no irrigation and by 25 % with double irrigation (water logging). Nitrogen fertilizer increased total N in *Kabuli* chickpea by nearly 90 %.
5. Nitrogen harvest index (based on above-ground N including the N in shed leaves) of *Kabuli* chickpea was relatively stable across irrigation levels with an average value of 0.52. However, the NHI in narrow-leafed lupin reduced from 0.65 with full irrigation to 0.45 with no irrigation.

6. Nitrogen accumulation efficiency, based on above-ground N including N in shed leaves, of *Kabuli* chickpea increased from 0.013 with full irrigation to 0.020 and 0.017 g N g⁻¹ DM with no irrigation and full irrigation with N fertilizer, respectively. However, the NAE of narrow-leaved lupin was not affected by irrigation levels or N fertilizer. With full irrigation the NAE of narrow-leaved lupin was 0.017 g N g⁻¹ DM.

7. There were close relationships between total DM and total N, and total N with seed N. Seed yield was closely related to total N and seed N. The CHI was related significantly to NHI.

Chapter 7

General Discussion

This study was conducted to examine the responses in growth, yield and N accumulation of *Kabuli* chickpea and narrow-leafed lupin to different levels of irrigation and N fertilizer applied at sowing. The irrigation applied ranged from no irrigation, half irrigation, full irrigation, double irrigation and a control, full irrigation with 150 kg N ha⁻¹. Responses of several physiological mechanisms including canopy development, radiation interception and radiation use efficiency (RUE) were also determined.

The results indicated that TDM and seed yield were significantly affected by both irrigation and legume species. Averaged over the two legumes, there was a threefold increase in TDM and seed yield in fully irrigated plots (Table 4.4). With full irrigation seed yield of *Kabuli* chickpea was 326 g m⁻² and that of narrow-leafed lupin was 581 g m⁻² (Figure 4.3). Increased TDM and seed yield in fully irrigated plants were related to increases in growth rate, pods plant⁻¹, seeds m⁻² (Chapter 4), LAI, LAD, total intercepted PAR and RUE (Chapter 5). Similar conclusions were made for lentil by McKenzie (1987), for field bean by Husain *et al.* (1988b) and for pinto bean by Dapaah *et al.* (2000).

Growing conditions during this project were drier and Penman evapotranspiration was 4 % higher than the long term mean (Figure 4.1). Irrigation gave more favourable conditions for crop growth. As a result, irrigation responses to full irrigation were higher than those reported by Husain *et al.* (1988a) for field bean and Anwar *et al.* (2003a) for *Kabuli* chickpea. The marked increases in crop growth rates in response to irrigation in this study (Table 4.1) support the results of Husain *et al.* (1988b) in field beans and other crops as discussed in Chapter 4. Maximum growth rates were 27.6 and 34.1 g m⁻² day⁻¹ for fully irrigated chickpea and narrow-leafed lupin, respectively. These values are similar to those for soybean (27 g m⁻² day⁻¹) reported by Loomis and Gerakis (1975) and for other C₃ crops reported by Monteith (1978) with a range of 34 to 39 g m⁻² day⁻¹.

Seed yield increases in response to irrigation were related to increased TDM and crop growth rate (Table 4.8 and 4.9). Similar relationships were reported by Husain *et al.* (1988a) and Anwar *et al.* (2003a). Dapaah (1997) suggested that greater TDM in response to irrigation could have provided sufficient assimilates for yield component increases. Development of pods and seeds was also dependent on the growth rate and dry matter accumulation (Husain *et al.*, 1988b). These results showed that seed yield was significantly

related to pods plant⁻¹, in narrow-leafed lupin and seeds m⁻² in both *Kabuli* chickpea and narrow-leafed lupin (Table 4.8). The two seed yield components were significantly related to TDM and crop growth rates (Table 4.9; Figure 4.5 and 4.6). Similar relationships have been reported for different species as indicated in Chapter 4. Muchow and Charles-Edwards (1982) and Pandey (1984) also emphasized the importance of critical assimilate supply in determining pod number in mungbean and chickpea. These results support the theory that a minimum rate of assimilate supply is required for reproductive growing points, while maintaining continuous meristem viability (Charles-Edwards, 1986; Guilioni *et al.*, 2003).

Total dry matter and seed yield increases in response to irrigation can be explained by increases in the LAI, LAD, total intercepted PAR and final RUE (Husain *et al.*, 1988b). These results here indicated a significant relationship between TDM, seed yield and these canopy and radiation interception attributes (Table 5.3). Similar findings have been reported in a range of grain legumes (McKenzie, 1987; Thomas and Fukai, 1995; Anwar, 2001). As discussed in Chapter 5, leaf growth and leaf elongation were significantly reduced by water stress through reductions in leaf cell division and expansion. With full irrigation, maximum LAIs in this work were significantly increased. Dapaah (1997) reported irrigation increased the maximum LAI of pinto bean by 89 %. Increased LAIs resulted in increased radiation interception. In this work, with full irrigation, crops achieved a closed canopy as they intercepted more than 95 % of incoming incident radiation at LAIs of 2.9 and 3 for *Kabuli* chickpea and narrow-leafed lupin, respectively (Chapter 5). In contrast, in non-irrigated plots the crops achieved a maximum fraction of radiation intercepted of less than 90 % as maximum LAIs were only 2.3 and 2.4 for *Kabuli* chickpea and narrow-leafed lupin, respectively. Muchow (1985a) reported that under water stress there was a reduction in the fraction of radiation intercepted in soybean and cowpea which was related to reduced leaf area.

Total intercepted PAR increased 31 % in fully irrigated plots (Table 5.2). Increased total intercepted PAR was a direct result of increases in LAD (106 % increase). Similar responses in total intercepted PAR to full irrigation have been reported by Husain *et al.* (1988b), by McKenzie and Hill (1991) and Anwar *et al.* (2003a). The low amount of total intercepted PAR in water stressed plots was attributed to low LAD which in turn was caused by slow canopy development, an accelerated rate of maturity and leaf senescence (Hsiao, 1993).

Total dry matter and seed yield reductions under water stress were not only caused by reduced total intercepted PAR but also by reduced RUE (Muchow, 1985a; Jamieson *et al.*, 1995; Thomas and Fukai, 1995). In this study, final RUE was significantly reduced in non-irrigated plots (Table 5.1). The reduction in RUE in non-irrigated plots might have been caused by the warmer conditions. As temperature increased, a net photosynthesis decline was associated with a substantial increase in respiration (Charles-Edwards and Charles-Edwards, 1970). In a review of several plant species, Bauer *et al.* (1975) also indicated there was reduced CO₂ uptake with heat stress. The reduction in RUE and net photosynthesis might have been responsible for the reduction in TDM and crop growth rates in the non-irrigated plots as suggested by Dapaah (1997).

Seed yield was reduced by 45 % with double irrigation (designed to produce water logging). In peas, Greenwood and McNamara (1987) reported that seed yield fell 12 % with double irrigation. Toker *et al.* (2007) reported that chickpea seed yield could be reduced by 100 % under water logging. Narrow-leafed lupin seed yield was reduced by 60 % when waterlogged for 2 weeks (Davies *et al.*, 2000c). Water logging led to stomatal closure (Jackson and Hall, 1987), reduced leaf gas exchange and thus photosynthesis (Davies *et al.*, 2000b), and reduced N fixation (Bacanamwo and Purcell, 1999). In this work, the reduction in final RUE of narrow-leafed lupin by double irrigation might have been caused by a reduction in these processes, which in turn resulted in seed yield reduction. Total N accumulated in narrow-leafed lupin by physiological maturity was reduced by 24 % (Chapter 6). This reduction may explain the inability to take up soil N and to assimilate N by symbiotic N fixation. This seed yield reduction could have also been caused by an N deficiency for seed development. The reduction in seed yield of *Kabuli* chickpea by water logging can not be explained by these mechanisms as RUE and total N accumulated in double irrigated plots were not significantly lower than in fully irrigated plots.

Seed yields of *Kabuli* chickpea and narrow-leafed lupin were not increased by N fertilizer (150 kg N ha⁻¹). Lack of response in seed yield has been reported by Bonfil and Pinthus (1995) and Walley *et al.* (2005) for chickpea and by Seymour and Brennan (1995) for narrow-leafed lupin. Sinclair and Horie (1989) argued that photosynthesis and RUE are increased by increases in specific leaf N. Sinclair and Muchow (1999) emphasized that leaf N and RUE can be increased by soil N fertility improvement. However, responses in crop growth rates and RUE to leaf N are typically curvilinear where RUE decreases if leaf N is below a ceiling point and RUE is not increased if leaf N is higher than the ceiling point

(Sinclair and Muchow, 1999). Based on these arguments, there are several indications in this study for explaining the reason for no response in seed yield to added N fertilizer. In *Kabuli* chickpea, even though the leaf N content was increased by additional N fertilizer (Figure 6.4), final RUE was not significantly different between the fully irrigated and the fully irrigated with N fertilizer plots (Chapter 5). In narrow-leafed lupin, additional N fertilizer did not increase final RUE or leaf N (Figure 6.5) and crop growth rates were not significantly increased by N fertilizer (Chapter 4). It is reasonable to accept that the lack of response in growth and RUE to additional N fertilizer might have been caused by a high leaf N content in fully irrigated plants (Chapter 5, discussion, radiation use efficiency), which may have reached a ceiling point. Wright *et al.* (1993) reported a ceiling value of $\geq 1.5 \text{ g N m}^{-2}$ leaf area in peanut. They indicated that there was no improvement in RUE when leaf N content was higher than this value. As discussed above, increased seed yield was related to increased TDM, crop growth rate and RUE. Hence, a high leaf N in fully-irrigated plots resulted in no response in TDM, crop growth and RUE to N fertilizer which might have been responsible for the lack of response in seed yield to added N fertilizer.

Crop harvest index (CHI) of *Kabuli* chickpea was not affected by irrigation. As discussed in Chapter 4, seed yield of *Kabuli* chickpea, grown under water stress, depends to a large extent on assimilates remobilized from vegetative parts (Khanna-Chopra and Singha, 1987; Davies *et al.*, 2000e). Seed yield of *Kabuli* chickpea in this study might have been derived from assimilate remobilization, thereby maintaining a CHI similar to that under full irrigation. In contrast, the CHI of narrow-leafed lupin was reduced in non-irrigated plots. Seed yield of narrow-leafed lupin, grown under water stress, depended less on assimilate remobilization from vegetative parts (Palta *et al.*, 2007). Also, vegetative growth of lupin continued during seed growth (Perry, 1975), which causes competition between reproductive and vegetative growth. Thus the water stress imposed by no irrigation in this study might have reduced available assimilates for seed growth by a reduction in total intercepted radiation, RUE, and dry matter accumulation and competition from concomitant vegetative growth during seed filling. All of these factors might have been responsible for a reduction in CHI in non-irrigated narrow-leafed lupin.

In this study, *Kabuli* chickpea did not nodulate. The crop, therefore, must have depended entirely on N uptake from the soil. Nitrogen accumulation was not significantly affected by different irrigation levels. The lack of responses in N accumulation to different irrigation levels supports the results of Purcell *et al.* (2004) and Bacanamwo and Purcell (1999). They reported that in non-nodulating soybean, there was no significant difference

in N accumulation rate between water stressed and well-watered plants. As soybean depended on nitrate supply, N accumulation was less affected by flooding (Bacanamwo and Purcell, 1999). Problematic chickpea nodulation was reported by Kosgey (1994). This might have been caused by incompatibility between the inoculum strain used and chickpea cultivars. Peoples and Herridge (1990) suggested that certain legumes species including *Cicer* only form nodules and fix N with a specific group of Rhizobium species. Sometimes, inoculum strains are not able to compete with ineffective rhizobia which have a well established soil population (Peoples and Herridge, 1990).

Narrow-leafed lupin formed nodules. Total N accumulation in the lupins was significantly reduced by both no irrigation and by double irrigation. As discussed in Chapter 6, N fixation by symbiosis represented the majority of total N accumulated in the lupins. The reduction in N accumulation might have been due to a reduction in N fixed. The literature indicates that N fixation is strongly affected by water deficit and excess (Chapter 2). The effect of water deficit or water excess on DM and N accumulation seem to be the same. The TDM of narrow-leafed lupin fell by 76 % and 30 % (Chapter 4); total N accumulation was reduced by 75 % and 25 % with no irrigation and double irrigation, respectively. There was also a close relationship between TDM production and total N accumulation (Chapter 6). The same magnitude of water deficit effect on DM and N accumulation in cowpea was reported by Chapman and Muchow (1985).

Nitrogen fertilizer increased total N in *Kabuli* chickpea by 90 % (Chapter 6). Increased total N in a chickpea crop in response to N fertilizer was also reported by McConnell *et al.* (2002). However, increased total N did not increase seed yield. McConnell *et al.* (2002) explained that the lack of response to N fertilizer was due to an inability to remobilize N from vegetative plant parts to seed. This can be caused by competition of excess vegetative growth at the expense of seed production (Bonfil and Pinthus, 1995). However, in this study it might not be a suitable explanation to describe the lack of response in seed yield to N fertilizer being due to excess vegetative growth as the CHI of *Kabuli* chickpea did not differ significantly between fully-irrigated plots and fully-irrigated plots with added N fertilizer (Chapter 4). However, it might be appropriate to explain the lack of response to N fertilizer in terms of crop growth rates and RUE, as discussed above.

Total N accumulation in narrow-leafed lupin was not increased by N fertilizer (Figure 6.3). This result is consistent with those of Evans *et al.* (1987) and Walley *et al.* (2005). Evans *et al.* (1987) reported that the lack of response in total N accumulated to N

fertilizer in lupin crops might be due to the plant ineffectiveness at absorbing N from the soil. Alternatively, Evans *et al.* (1987) and Walley *et al.* (2005) suggested that additional N did not increase total N but substituted for the amount of N fixed by symbiosis. In this study, the amount of N fixed was not measured by a suitable technique i.e. ^{15}N dilution. However, there was an indication of a negative effect of N fertilizer on N fixation. The amount of N in nodules of fully-irrigated plots with N fertilizer was significantly lower than in fully-irrigated plots. As N concentration was relatively stable between full irrigation and the full irrigation with N fertilizer treatments, the reduced N accumulated in nodules of fully irrigated plots with N fertilizer was related to a reduction in nodule number and dry weight. These results support the concept that N fixation is strongly affected by soil NO_3 (Peoples and Herridge, 1990).

The responses in NHI of *Kabuli* chickpea and narrow-leafed lupin to irrigation level were very similar to the CHI responses. While the NHI (based on above-ground N including shed leaves) of *Kabuli* chickpea was relatively stable the NHI of narrow-leafed lupin was significantly reduced in non-irrigated plots. Reduction in NHI caused by water stress is reported in the literature (Chapter 6). Reduction in NHI was related to low N partitioning to seed (Chapman and Muchow, 1985). De Vries *et al.* (1989) suggested that low N partitioning to seed might be caused by low sink size, in water stressed crops, as the number of pods and seeds was significantly reduced. Using N labelling Davies *et al.* (2000e) reached a similar conclusion.

These results indicated that the total N was significantly related to total DM accumulation and seed yield and seed N was also significantly related to TDM and total N accumulation (Table 6.9; Figure 6.9, 6.10 and 6.11). This result supports the findings of Muchow *et al.* (1993) for soybean, mungbean and cowpea; of Pengelly *et al.* (1999) for phasey bean (*Macroptilium lathyroides* (L.) Urban), vigna (*Vigna triobata* (L.) Verdc.) and Sesbania (*Sesbania cannabina* Retz.) and of Ayaz (2001) for temperate legumes; *desi* chickpea, lentil, narrow-leafed lupin and pea. Muchow *et al.* (1993) suggested that these robust relationships have several implications for modelling purposes. Total N accumulation can be modelled by using dry matter accumulation. Seed yield and seed N can also predicted using their proportions to dry matter and accumulated N (Muchow *et al.*, 1993).

The different N content in various plant plants of grain legumes gives an indication of how much N is harvested in the seed and how much N is contributed to the cropping system in legume residues (Howieson *et al.*, 1998). Pate and Farquhar (1988) indicated

failure of NHI (based only on above-ground biomass) to include the amount of N from below-ground materials and litter which contributes to the soil N pool. They reported a NHI of a narrow-leafed lupin crop of 0.63 if it was estimated from the ratio of seed N to total N in the shoot at final harvest. However, the NHI decreased to 0.48 when it is based on the ratio of seed N to the total N in shoots, roots and shed leaves. In this study, NHI of *Kabuli* chickpea decreased from 0.55 to 0.50 and the NHI of narrow-leafed lupin decreased from 0.70 to 0.51 (Table 6.8) when the methods of estimation were changed as described above. Pate and Farquhar (1988) argued that the difference between NHI, estimated from the two methods, indicates a significant contribution of legume N to cropping systems in the forms of roots, nodules and litter; hence, the two forms of NHI should be computed to obtain a greater understanding of the N dynamics in grain legumes.

The present results have several implications for agronomic practices for *Kabuli* chickpea and narrow-leafed lupin. Seed yield was substantially increased by full irrigation. Increased seed yield was significantly related to increases in total DM, weighted mean absolute growth rates and maximum growth rates. These variates took account of the crop performance during the whole growth cycle. This can imply that seed yield reduction caused by a water deficit occurring at a particular growth stage might not be recovered by irrigation at another stage. The crops need to be irrigated whenever they experience a water deficit greater than a given limiting deficit. Water logging reduced seed yield; therefore, irrigation should be done only at an amount that replaces the water deficit to avoid water logging. As total DM is strongly related to total N accumulation irrigation to increase seed yield might also be important to increase N accumulation, in particular, in crops which are symbiotically fixing N as discussed in Chapter 6.

Added N fertilizer did not increase seed yield or seed N. The reason for this lack of response in seed yield to N fertilizer is discussed above. Application of N fertilizer only substitutes for the amount of N fixed (Evans *et al.*, 1987; Walley *et al.*, 2005). The effect of N fertilizer on N fixation in *Kabuli* chickpea can not be determined because of its failure to nodulate. However, in narrow-leafed lupin N fertilizer might have replaced the amount of N fixed. Hence, N fertilizer application is not a good option for increasing seed yield in narrow-leafed lupin and it can minimize the potential role of narrow-leafed lupin in fixing N from the atmosphere for its own growth and producing an N residue for the cropping system.

Conclusions

1. Irrigation trebled seed yield of the two legumes compared to no irrigation. With full irrigation, seed yields were 369 and 649 g m⁻² for *Kabuli* chickpea and narrow-leafed lupin, respectively. However, irrigation at double the amount of water deficit reduced seed yield by 45 %.
2. Growth, TDM and seed yield were not increased by added N fertilizer (150 kg N ha⁻¹) and yield components and HI did not respond to this additional N.
3. Increased seed yields were related to increased TDM, crop growth rates, seeds pod⁻¹ and seeds m⁻². To obtain high potential yield, crops should be irrigated whenever they need water due to a soil moisture deficit.
4. Irrigation increased LAI, LAD and total intercepted PAR and final RUE. With full irrigation, final RUEs were 1.49 and 2.17 g DM MJ⁻¹ for *Kabuli* chickpea and narrow-leafed lupin. The TDM and seed yield were strongly related to LAD, total intercepted PAR and final RUE.
5. In *Kabuli* chickpea, total N accumulation (based on above-ground N including N in shed leaves and roots and nodules) was not affected by irrigation level. With full irrigation, total N was 17.7 g m⁻². Nitrogen fertilizer increased total N in non-nodulated *Kabuli* chickpea by nearly 90 %.
6. Nitrogen accumulation in narrow-leafed lupin was strongly affected by irrigation. Fully-irrigated narrow-leafed lupin produced 45.9 g N m⁻². This was reduced by 75 % and 25 % with no irrigation and with double irrigation. Nitrogen fertilizer did not increase total N in narrow-leafed lupin.
7. There was a close relationship between seed yield and total N, and seed N. Total dry matter was also significantly related to total N and seed N. Crop harvest index was closely related to NHI.

Recommendations for future research

There is a requirement for further research in this area before a full understanding can be obtained to develop a legume model to predict growth, yield and N contribution to mixed cropping systems. Further research should focus on:

1. Determining the physiological mechanisms responsible for reduction in seed yield by water logging i.e. reductions in photosynthesis, RUE and nutrient assimilation.
2. Quantifying the contribution of stored assimilate remobilized from leaves and stems to seeds and the effect of environmental factors on assimilate remobilization.
3. Examining the effect of the reduction in N in leaves and stems caused by remobilization on total intercepted PAR and RUE during seed development, and final seed production.
4. Determining the amount of N fixed and N uptake from the soil using ^{15}N isotope dilution, how legumes change from dependency on fixed N from the atmosphere to that on soil N uptake when legumes are under environmental stress.
5. Identifying the suitable *Rhizobium* strains for *Kabuli* chickpea for Canterbury and environmental factors i.e. soil nitrate which can affect nodulation and N fixation.

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