

**CANOPY ARCHITECTURE AND PLANT DENSITY EFFECT IN
SHORT-SEASON CHICKPEA (*CICER ARIETINUM* L.)**

A Thesis submitted to the College of Graduate Studies and Research
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in the Department of Plant Sciences
University of Saskatchewan
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Abstract

Chickpea (*Cicer arietinum* L.) production on the semi-arid Canadian Prairies is challenging due to a short growing season and low and variable moisture. The current recommended chickpea population density of 44 plants m^{-2} is based on preliminary studies and a narrow range of 20 to 50 plants m^{-2} . The aims of this study were to i) determine optimum population density of varying chickpea canopy types, i.e., leaf type and growth habit, by investigating seed yield responses at 30 to 85 plants m^{-2} and ii) identify desirable parental traits for breeding programs by assessing growth and yield parameter responses to varying leaf types and growth habits at a range of population densities. Field experiments were conducted from 2002 to 2005. Canopy measurements and calculated variables included light interception, biomass, growth rate, seed yield, harvest index, ascochyta blight severity and radiation- and water use efficiencies.

The plant density which produced the highest seed yield when averaged over years for each location for each treatment revealed that a plant density of at least 55 plants m^{-2} produced a 23% to 49% seed yield increase above that of the currently recommended plant density. This indicates that a higher seed yield average over the long term in spite of periodic low seed yield episodes will be more profitable to producers. Increasing plant density increased lowest pod height significantly in all except one location-year but did not explicitly increase ascochyta blight severity or decrease individual seed size. This suggests that increasing the recommended chickpea plant density on the Canadian Prairies will increase seed yield but would neither negatively impact individual seed size nor ascochyta blight severity, especially, when combined with good agronomic practices.

Fern-leaved cultivars had significantly higher maximum intercepted light (62 to 91%), seed yield (136 to 369 g m^{-2}), harvest index (0.33 to 0.53), yield-based water use efficiency (0.56 to 1.06 $\text{g m}^{-2} \text{mm}^{-1}$) and lower ascochyta blight severity (3 to 27%) than the unifoliolate cultivars in all location-years. The fern-leaved cultivars also tended to show significantly higher cumulative intercepted radiation (221 to 419 MJ m^{-2}) and biomass (306 to 824 g m^{-2}) but leaf type showed no consistent effect on radiation use efficiency.

Cultivars with bushy growth habit generally performed better regarding maximum intercepted light (62 to 90%), cumulative intercepted radiation (233 to 421 MJ m⁻²), biomass (314 to 854 MJ m⁻²), seed yield (120 to 370 g m⁻²), harvest index (0.37 to 0.50), yield-based water use efficiency (0.56 to 1.06 g m⁻² mm⁻¹) and ascochyta blight severity (7 to 36%) than the erect cultivars. The overall performance of the spreading cultivar was generally intermediate between the bushy and erect cultivars except for ascochyta blight severity where the spreading cultivar exhibited significantly lower disease severity (3 to 36%). Radiation use efficiency was generally not influenced by growth habit.

Increasing plant population density generally increased intercepted light, biomass and cumulative intercepted radiation on each sampling day after seeding resulting in a general increase in seed yield. Harvest index, however, remained constant and ascochyta blight severity was generally stable but radiation use efficiency decreased with increasing population density. Chickpea cultivars with fern leaves and bushy growth habit at higher than currently recommended population densities would best utilize the limited resources of the short-season Canadian prairie environment to maximize and stabilize seed yield.

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Abbreviations

CDC	Crop Development Center, University of Saskatchewan
CGR	Crop Growth Rate
DAS	Days After Seeding
E_s	Soil Evaporation
ET	Evapotranspiration
FAO	Food and Agricultural Organization
HI	Harvest Index
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
LI	Light Interception
PAR	Photosynthetically Active Radiation
PPD	Plant Population Density
RI	Cumulative Intercepted Radiation
RUE	Radiation Use Efficiency
SC	Swift Current
SPG	Saskatchewan Pulse Growers
STN	Saskatoon
T	Transpiration
TE	Transpiration Efficiency
USDA	United States Department of Agriculture
WU	Water Use
WUE	Water Use Efficiency
WUE_{biomass}	Biomass-Based Water Use Efficiency
WUE_{seed}	Seed Yield-Based Water Use Efficiency

1.0 INTRODUCTION

Chickpea (*Cicer arietinum* L.) is one of the oldest annual grain legumes in the world. Believed to have originated in Turkey and then spread to Asia, the Middle East and North Africa, it is currently grown in East and South Africa, Europe, Australia and the Americas including Canada. Chickpea is grown primarily for human consumption and it is an important source of protein and complex carbohydrates in human diets, especially in developing countries. Globally, chickpea is the third most important dietary grain legume after dry bean (*Phaseolus vulgaris*) and field pea (*Pisum sativum* L.) (National Academy of Science, 1994).

Commercial production of chickpea in Canada began around the mid-nineteen nineties and production rose rapidly from 1000 tonnes 1995 to 455,000 tonnes in 2001 (FAO Stats, 2008). Production fell to 51,000 tonnes in 2004 due to the fungal disease ascochyta blight (*Ascochyta rabiei* (Pass.) Labrousse), poor weather conditions and reduction in market price in addition to a general lack of agronomic knowledge (Gan et al., 2003a) and management recommendations. Canadian production of chickpea has since rebounded to 225,000 tonnes in 2007 (FAO Stats, 2008) as a result of increased seeded area due to higher market prices, increased seed yield and availability of improved ascochyta resistant and adapted cultivars.

More than 90% of the Canadian chickpea production is concentrated in the semi-arid region of the Canadian Prairies (Gan and Noble, 2000). Incorporation of chickpea as a specialty crop in the largely cereal-based cropping systems of the Canadian Prairies offers many advantages to growers. Chickpea is a legume and therefore fixes atmospheric nitrogen to supplement the nitrogen supply from the soil, thus improving soil fertility and reducing fertilizer costs. Inclusion of chickpea in rotations of cereal cropping systems also extends rotation cycles as well as providing a means of disease- and pest-cycle break. Chickpea is also deep-rooted compared to other legumes (Hamblin and Hamblin, 1985; Hamblin and Tennant, 1987; Gregory, 1988) and hence has the ability to tap soil moisture from greater depths which may not be accessible to shallow-rooted crops. In addition to the foregoing agronomic suitability of chickpea to the Canadian Prairies, average Canadian chickpea yields are higher as compared to average world yields (FAO, 2005). Market prospects are also promising, e.g., Canada was the third largest

chickpea exporting country in 2002, all of which account for the strong interest in the chickpea industry in Western Canada.

Chickpea has been cultivated for centuries in many semi-arid regions of the world (Siddique and Sykes, 1997). Crop production in such areas as well the Canadian Prairies is challenging due to low and variable moisture availability. The Canadian Prairies poses additional challenges of a short growing season (May to August) and limited heat units. Also, chickpea is traditionally grown on stored moisture but on the Canadian Prairies up to 67% of annual precipitation falls within the growing season (Longley 1972; Dey 1982). The use of suitable cultivars and agronomic practices to maximize the limited resources of the short growing season is critical for greater and stable chickpea yields on the Canadian Prairies.

Crop yield is a function of radiation intercepted over the growing season, the efficiency of converting the intercepted radiation into biomass and the partitioning efficiency of biomass to seed yield (Sinclair, 1993). Donald (1962) termed the conversion of biomass to seed yield as harvest index (HI). In time-constrained production systems, therefore, maximizing the limited solar radiation could lead to yield improvement. Factors affecting radiation interception include plant population density (PPD) and plant canopy elements such as leaf type and growth habit which subsequently influences canopy photosynthesis culminating in seed yield. Low and variable rainfall are frequently the main limiting factors in crop yield on the Prairies (Cutforth et al., 1999). Crops with high water use efficiency (WUE), i.e., the amount of seed yield or biomass per unit water use (WU) will be at an advantage in such conditions. Most advances in more efficient crop WU are obtained first by reducing soil evaporation and then increasing the fraction used by the crop in transpiration.

Two leaf types (fern and unifoliate) and three growth habits (bushy, erect and spreading) are exhibited by chickpea cultivars grown on the Canadian Prairies. The pinnate compound fern leaves are expected to have better seasonal radiation capture by allowing deeper penetration of radiation into the canopy than the simple unifoliate leaves. The more branched bushy and spreading growth habits may have earlier and greater canopy closure than the erect growth habit. This may result in differences in PPD required for maximum yield by the contrasting leaf types

and growth habits. The rate of canopy development is a combination of leaf type, growth habit and PPD. Chickpea canopies with differing rates of canopy development may affect light interception (LI), cumulative intercepted radiation (RI) and radiation use efficiency (RUE) as well as WU and WUE.

The current recommended chickpea PPD for the Canadian Prairies is 44 plants m⁻² based on preliminary studies (Saskatchewan Pulse Growers, 2002), a subset of four cultivars available at the time and a narrow agronomic range of 20 to 50 plants m⁻² (Gan et al., 2003a). Traditionally, the lowest PPD for maximal seed yield is chosen, but for short-season production, higher PPDs may be required as shown in short-season soybean (*Glycine max* L. Merr) production systems (Ball et al., 2000).

Ayaz et al. (2004a) reported significant increases in green area index, RI and RUE with increasing PPD while biomass, seed yield and HI were all strongly correlated with RI under sub-humid temperate conditions. Different pea leaf types have also shown significant differences in WU at high moisture stress (Alvino and Leone, 1993) and fern-leafed chickpea cultivars had significantly higher crop growth rate (CGR) than the unifoliolate-leafed cultivars (Li et al., 2006). Prostrate-spreading chickpea increased WUE compared to erect forms, although growth habit and phenology were confounded (ICARDA, 1982). Information is, however, lacking on both chickpea seed yield response at high PPDs and the incorporation of canopy habits in recently released cultivars, namely the effect of leaf type and growth habit on growth and yield parameters for the Canadian Prairies.

The objectives of this research were to:

- (i) determine the optimum PPD of varying chickpea canopy types, i.e., leaf type and growth habit) on the Canadian Prairies by investigating seed yield responses to a wide range of PPDs (30 to 85 plants m⁻²)
- (ii) assess LI, RI, biomass, RUE, seed yield and HI of chickpea cultivars varying in leaf type and growth habit at a range of PPDs and
- (iii) evaluate the effects of varying canopy traits (leaf type and growth habit) and PPD on chickpea WU and WUE on the Canadian Prairies

The ultimate goal of this research is to identify the best parental traits for radiation capture, growth, seed yield and WUE for chickpea breeding programs for the temperate short-season Canadian prairie environment.

2.0 LITERATURE REVIEW

2.1 Chickpea Production on the Canadian Prairies

Chickpea (*Cicer arietinum* L.) is a diploid ($2n = 16$), self-pollinating, cool season annual of the family Leguminosae grown mainly for human consumption. Globally, chickpea is the third most important dietary grain legume after dry bean (*Phaseolus vulgaris* L.) and field pea (*Pisum sativum* L.) (National Academy of Science, 1994). Early production of chickpea was centered around Asia, the Middle East and North Africa but it is currently grown in East and South Africa, Europe, Australia and the Americas including Canada.

Chickpea production in Canada was first reported in the mid-nineteen nineties and rose quickly to 455,000 tonnes in 2001 (FAO Stats, 2008). Canadian chickpea production was then adversely affected by ascochyta blight, poor weather conditions and low market prices, in addition to a paucity of agronomic knowledge (Gan et al., 2003a) resulting in a reduction in production to 51,000 tonnes in 2004. Production of chickpea has since risen to 225,000 tonnes in 2007 (FAO Stats, 2008) as a result of increased seeded area due to good market prices, increased seed yield and availability of improved ascochyta resistant and adapted cultivars.

Chickpea as a specialty legume crop offers many advantages to the largely cereal-based cropping system of the Canadian Prairies. As a legume, chickpea fixes atmospheric nitrogen to improve soil fertility and thus reduce fertilizer costs. Inclusion of chickpea in crop rotations extends rotation cycles and provides a means of disease and pest cycle break. Chickpea is also deep-rooted compared to other legumes (Hamblin and Hamblin, 1985; Hamblin and Tennant, 1987; Gregory, 1988) and hence has the ability to tap soil moisture from greater depths which may not be accessible to shallow-rooted crops. In addition, chickpea is also drought tolerant and therefore highly suitable to the semi-arid environment of the Canadian Prairies. Chickpea production and area seeded to chickpea increased the most amongst all specialty crops in Saskatchewan in 2007 (Saskatchewan Ministry of Agriculture, 2008). Average yield also increased by 4% in Saskatchewan in 2007 (Saskatchewan Ministry of Agriculture, 2008). Average Canadian chickpea yields are also higher than the world average (FAO, 2005) and Canada is among the top

five world chickpea exporting countries, all of which point to positive prospects for the Canadian chickpea industry.

Chickpea production in Canada is concentrated in the semi-arid regions of the Canadian Prairies, i.e., the Brown Soil and Dark Brown Soil zones, where over 90% of the crop is produced (Gan and Noble, 2000). Production of chickpea on the Canadian Prairies is challenging due to low and variable moisture availability, similar to many semi-arid regions of the world where chickpea has been cultivated for hundreds of years (Siddique and Sykes, 1997). The Canadian Prairies pose additional challenges of a short growing season (May to August) and limited heat units. Also, chickpea is traditionally grown on stored moisture but on the Canadian Prairies up to 67% of annual precipitation falls within the growing season (Longley 1972; Dey 1982). The use of cultivars with suitable canopy traits and agronomic practices to maximize the limited resources of the short growing season is critical for greater and stable chickpea seed yields on the Canadian Prairies.

2.2 Chickpea Seed Classes

Chickpea is classified into 2 seed or market classes, namely desi and kabuli chickpea. Desi chickpea is grown in the Indian subcontinent and East Africa and have smaller and angular seeds which range in color from yellow to black. Desi chickpea also have colored flowers. Kabuli chickpea is grown in the Mediterranean region and in Central and South America and have larger and rounded seeds which are white to cream colored. Kabuli chickpea have white flowers (Muehlbauer and Singh, 1987). Desi and kabuli chickpea are both currently grown on the Canadian Prairies.

2.3 Chickpea Canopy Architecture

Canopy architecture refers to the distribution, orientation, size and shape of plant organs such as leaves, stems, branches and flowers (Wells and Norman, 1991). Canopy architecture therefore essentially affects crop functions such as light interception (LI) and evapotranspiration and eventual biomass accumulation and seed yield production. In this research, canopy architecture elements evaluated are leaf type (i.e., leaf morphology or shape), growth habit (i.e., individual plant shape) and number of nodes on main stem as a proxy for number of primary branches.

2.3.1 Leaf Type in Chickpea

Normal leaf type in chickpea is pinnately compound, i.e. fern leaf type (Fig. 2.1). A mutant simple leaf type, i.e., unifoliate (Fig. 2.1), was first described by Ekbote (1937). The simple unifoliate leaf trait has been incorporated into chickpea cultivars, e.g., Dwelley, Evans and Sanford by the breeding program of the United States Department of Agriculture (USDA) and CDC Diva and CDC Xena by the breeding program of the Crop Development Centre (CDC) of



Fig. 2.1 Leaf types in Chickpea (A) Fern and (B) Unifoliate

the University of Saskatchewan in Canada. Several variants of the fern and unifoliate leaf types exist and have been reviewed by Muehlbauer and Singh (1987). Pundir et al. (1990) grouped the world chickpea collection at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) into three major leaf type classes based on differentiation of the lamina, namely normal (pinnate or fern), simple (unifoliate) and multipinnate with uni-, bi-, or tri-pinnate leaflets. Pundir et al. (1990) and Danehloueipour et al. (2008) reported that the three leaf types are controlled by two genes.

Two leaf types (fern and unifoliate) are exhibited by chickpea cultivars grown on the Canadian Prairies. The fern leaves are expected to have better seasonal radiation capture by allowing deeper penetration of solar radiation into the canopy than the simple unifoliate leaves. Monsi and Saeki (1953) modeled the relationship between canopy light penetration and leaf area using Beers-Lambert law. In soybean, leaf and branch arrangement that promoted increased light penetration into the canopy resulted in greater seed yield (Shaw and Weber, 1967).

Limited studies have, however, explored the effect of leaf type on LI, biomass accumulation and seed yield production in chickpea. Studies on the Canadian Prairies using a limited number of chickpea cultivars have shown that cultivars with fern leaves produced significantly higher seed yield than cultivars with unifoliate leaves (Li et al., 2006; Gan et al., 2007). Elsewhere, at ICRISAT-Patancheru in India, Srinivasan et al. (2006) also reported significantly higher seed yield in chickpea breeding lines with fern leaves than lines with unifoliate leaves. Conversely, recent studies from Australia have reported no seed yield advantage for either leaf type (Bonfil et al., 2007; Danehlouepour et al., 2008). Bonfil et al. (2007), however, acknowledged that leaf characteristics and rate of biomass accumulation may be important determinants of seed yield under short-season conditions. Differences in LI between the canopies of the two leaf types may result in differences in biomass accumulation, seasonal intercepted radiation and seed yield. Under the short-season production system of the Canadian Prairies, therefore, the leaf type that maximizes the limited solar radiation resource may be required to contribute to higher seed yield.

2.3.2 Growth Habit in Chickpea

Growth habit in chickpea is controlled by a single Mendelian gene (Muehlbauer and Singh, 1987). Growth habit is influenced by branching in chickpea and branching is a primary factor in determining the number and position of flowers and pods, and thus seed yield (Muehlbauer and Singh, 1987). Growth habit in chickpea varies from erect, with primary branch angles of 0 to 15° from vertical, through semi-erect or bushy, with primary branch angles of 16 to 60° from vertical, to spreading, with primary branch angles of 61 to 80° from vertical (Fig. 2.2) and prostrate, with branches lying flat on the ground (Singh and Diwakar, 1995; PPV & FRA, 2007).

Under Mediterranean conditions of south Spain, Rubio et al. (2004) found seed yield of chickpea lines with bushy growth habit to be higher than that of lines with erect growth habit and attributed this to a higher number of reproductive sites in the bushy lines. Similarly, Knights (1984) reported higher seed yield in semi-erect chickpea lines than erect lines in Australia. However, Siddique and Sedgley (1985) proposed a reduced branching or erect chickpea growth habit ideotype at high densities for the short-season Mediterranean type environment of southwestern Australia. This was to increase seed yield through increasing overall HI by eliminating

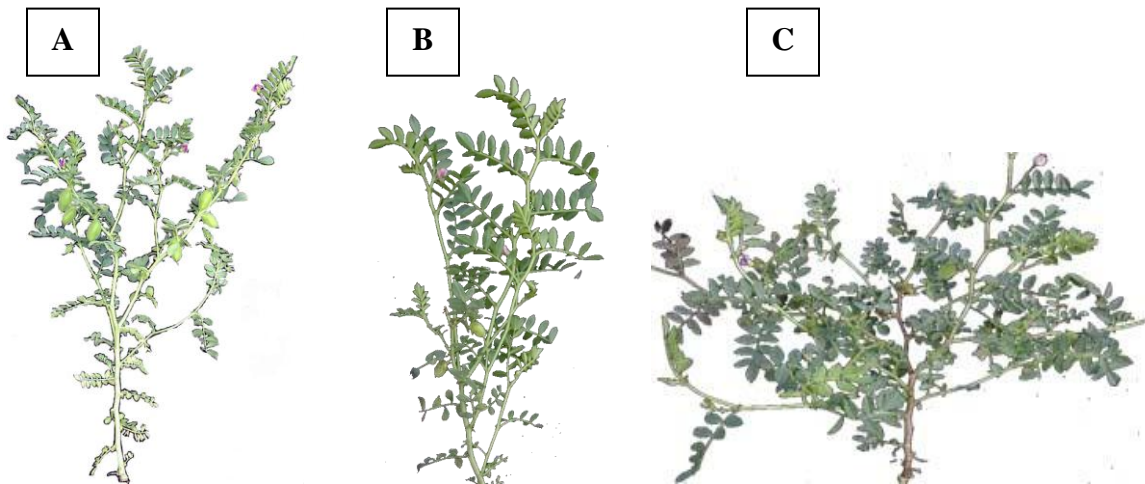


Fig. 2.2 Growth habits in chickpea (A) Bushy, (B) Erect and (C) Spreading

less productive basal branches. Earlier, Saxena and Sheldrake (1980) found no seed yield advantage of non-branching, erect chickpea cultivars at increased PPDs in India.

Crop ideotypes address specific conditions of a target environment and so a single ideotype may not be ideal for the many and varied environments where chickpea is currently grown worldwide. On the Canadian Prairies where about 67% of annual precipitation occurs during the growing season, chickpea cultivars with growth habits that will lead to early and greater canopy closure in order to reduce evaporative soil water loss and maximize solar radiation capture may be required to optimize seed yield. The 14-day delay in attainment of maximum leaf area index by the reduced canopy in the Siddique and Sedgley (1985) study would therefore be very costly regarding solar radiation capture and direct soil evaporation on the short-season Canadian Prairies.

Three growth habits, i.e., bushy, erect and spreading, are exhibited by chickpea cultivars available on the Canadian Prairies. The more branched bushy and spreading growth habits may have earlier and/or greater canopy closure than the erect growth habit. Chickpea canopies with differing rates of canopy development may affect LI, RI and RUE as well as WU and WUE.

2.4 Chickpea Plant Population Density

The PPD that produces maximum yield or optimum PPD of crops, including, chickpea, is affected by both genotype, environment and their interaction. A range of optimum PPD has therefore been reported for various chickpea cultivars and environments. Beech and Leach (1989) concluded that a minimum PPD of 40 plants m^{-2} would be required for maximum seed yield in south-eastern Queensland, Australia. Jettner et al. (1999) suggested an optimum PPD of 50 plants m^{-2} for most chickpea crops in south-western Australia but a PPD of more than 70 plants m^{-2} under high-yielding conditions to maximize profit.

Various models have been used to describe seed yield in chickpea. Generally, seed yield increases to a maximum and then either remains flat or decreases as PPD increases. Both models were exemplified in the study by Gan et al. (2003a) where under stubble conditions, seed yield approached a peak which was attributed to a lack of sufficient moisture whereas under summer fallow conditions seed yield peaked and then dropped. Gan et al. (2003a) tested a limited number of cultivars (i.e. four cultivars) available at the time over a limited range of PPDs (i.e. 20 to 50 plants m^{-2}). With more cultivars with varying canopy traits currently available, the PPD that produces the maximum seed yield on the Canadian Prairies needs to be determined in order to maximize the profit margins for producers. Varying chickpea canopy types may require different PPD to maximize seed yield. For example, a higher PPD is required by leafless cultivars in pea than either semi-leafless or conventional types (Heath and Hebblethwaite, 1987). The higher PPD of the leafless cultivars allows production of a canopy size which is adequate for maximum radiation interception and high seed yields. However, Heath et al. (1991) found no differences in optimum densities between semi-leafless and leafed peas.

The current recommended chickpea PPD for the Canadian Prairies is 44 plants m^{-2} based on preliminary studies (Saskatchewan Pulse Growers, 2000) and a subset of four cultivars available at the time and a narrow agronomic range of 20 to 50 plants m^{-2} (Gan et al., 2003a). Traditionally, the lowest PPD for maximal seed yield is chosen, but for short-season production, higher PPDs may be required. In both short-season soybean (Ball et al., 2000) and short-season maize (Edwards and Purcell, 2005), PPDs greater than that required for the full-season crops were required to maximize seed yield. Under late-sowing conditions where the season becomes

shorter than normal, higher than recommended chickpea PPDs have been shown to produce seed yields comparable to the recommended PPDs (Ali, 1988; Shakhawat and Sharma, 1986).

Chickpea competes poorly with weeds, therefore a higher PPD than currently recommended may also provide an additional advantage of weed control through a reduction in light available below the canopy for use in weed growth. Less weed pressure in chickpea resulted in higher biomass accumulation and ultimate seed yield (Bhan and Kukula, 1987). However, higher chickpea PPD may result in higher disease severity as reported by Chang et al. (2007) although ascochyta severity increased with increasing PPD in some, but not all, cultivars of chickpea on the Canadian Prairies Gan et al. (2007).

2.5 Light Interception, Cumulative Intercepted Radiation and Radiation Use Efficiency in Chickpea

Solar radiation drives the conversion of carbon dioxide and water to organic carbon assimilates in plants. Therefore, maximizing interception of available solar radiation to maximize biomass accumulation and subsequent efficient partitioning of biomass to seed yield is crucial to crop production, especially under short-season production systems. Under normal growing conditions, radiation available and the length of time a crop grows determines biomass accumulation (Sinclair, 1993). Monteith (1977) established a linear relationship between LI and biomass accumulation and Gallagher and Biscoe (1978) and Sinclair (1993) related seed yield to the product of RI, RUE and HI. The RI is intercepted radiation accumulated over the length of the growing season and RUE defines the efficiency of the crop in the use of radiation for biomass accumulation while HI is the partitioning efficiency of biomass to seed yield. Within species, RUE shows little variation (Wilson, 1967; Gallagher and Biscoe, 1978; Sinclair and Muchow, 1999), thus, increasing either RI and/or HI should result in an increase in seed yield.

The amount of light that can be intercepted by a crop is determined by the length of a growing season in addition to the latitude of the location (for daylength and incoming radiation). For a given latitude, a crop can improve its intercepted radiation and hence, RI over the growing season by early season radiation capture through early season canopy development (Sinclair, 1993; Mwanamwenge et al., 1997; Richards et al., 2002), early seeding (Hughes et al., 1987;

Anwar et al., 2003), high PPD (Shibles and Weber, 1966, and Leach and Beech, 1988; Purcell et al., 2002; Ayaz et al., 2004a) and canopy characteristics that contribute to efficient LI (Hughes et al., 1987).

Mwanamwenge et al. (1997) identified early canopy development factors such as high leaf expansion rates and large leaves led to high absorbed PAR and canopy cover in a short-season Mediterranean environment. Chickpea, however, had the lowest leaf expansion rate and maximum leaf size and therefore the lowest absorbed PAR as compared with the other crops studied, i.e., faba bean (*Vicia faba* L.), field pea and narbon bean (*Vicia narbonensis* L.).

Shibles and Weber (1966) found that increasing soybean PPD increased leaf area index, LI and early canopy closure and while biomass accumulation correlated with LI, seed yield did not correlate with LI and biomass due to differences in HI. Under low latitude conditions, Purcell et al. (2002) reported early canopy closure at higher PPD in soybean which resulted in greater RI. End of season biomass showed a positive linear relationship to RI up to about 400 MJ m⁻² after which the response was curvilinear and RUE decreased with increasing PPD.

Hughes et al. (1987) reported similar RI and biomass production between erect and prostrate chickpea lines but the RUE was significantly higher for the erect lines than the prostrate lines in northern Syria. Plant population density also had minimal effect on biomass production, but high PPD was advantageous over lower PPD with respect to RI. Radiation use efficiency was, however, higher at lower PPD than at higher PPD.

Data on the effects of PPD and canopy architecture on LI, RI and RUE in chickpea on the Canadian Prairies and under high latitude temperate environment conditions in general are lacking. Knowledge on the capture and utilization of the limited solar radiation by varying canopy types and PPDs on the Canadian Prairies will be valuable in adapting and managing crops in such environments.

2.6 Water Use and Water Use Efficiency in Chickpea

Water use efficiency is crop biomass or seed yield per unit water use (WU) and it is a widely studied crop physiological characteristic (Angus and van Herwaarden, 2001) and continues to be of great interest to agriculturists, especially now that crop production expands to lands with marginal moisture to meet growing food demands of an ever growing world population. Low and variable rainfall are frequently the main factors limiting crop yield on the Prairies (Cutforth et al., 1999) and dryland cropping systems in general. Crops with high water use efficiency will therefore be at an advantage in such environments (Passioura, 1977; Ludlow and Muchow, 1990; Hatfield et al., 2001).

Passioura (1977) related crop seed yield to WUE and WU under limited water supply as

$$\text{Yield} = \text{WU} \times \text{WUE} \times \text{HI} \quad [2.1]$$

where WU or evapotranspiration (ET) is the water use via plant transpiration (T) and direct evaporation from soil surface (E_s), WUE is WUE based on biomass, i.e., ($\text{WUE}_{\text{biomass}}$) calculated as biomass divided by seasonal WU and HI is harvest index, i.e., seed yield divided by total seasonal biomass. Water use efficiency based on seed yield (WUE_{seed}) which is seed yield divided by seasonal WU is also reported in the literature and it serves as an adequate comparator where biomass data are unavailable. In drought-prone environments, improving one or more of the three yield parameters in equation 2.1, either through breeding or agronomic practices, may increase yield (Passioura, 1977).

Richards et al. (2002) showed that $\text{WUE}_{\text{biomass}}$ could be improved by decreasing E_s or increasing T based on the equation

$$\text{WUE}_{\text{biomass}} = \frac{\text{TE}}{1 + E_s/T} \quad [2.2]$$

where TE is transpiration efficiency, i.e., biomass production per unit water transpired. Crops depending on stored moisture improve WUE through TE while crops using in-season precipitation improve WUE effectively by decreasing soil evaporation (Richards et al., 2002). On the Canadian Prairies, up to two-thirds of annual precipitation falls within the growing season

from May to August (Longley, 1972; Dey, 1982), therefore, reducing E_s should contribute to higher seed yield through an increased WUE.

The rate of canopy development is influenced by a combination of leaf type, growth habit and plant population density (PPD). Chickpea canopies with differing rates of canopy development may affect crop WU, biomass accumulation and WUE. Crops that do not develop rapid leaf area early in the season tend to lose available soil moisture to soil evaporation. More water is used in crop T by increased crop vigor through high PPD, large seed size, root nutrition and improved seeding establishment (Richards, 2002). However, increased pre-anthesis WU may offset any seed yield gains due to lack of moisture during grain fill (Angus and van Herwaarden, 2001). On the Prairies, a strategy of high WU before anthesis may be advantageous because of the short growing season and the indeterminate habit of chickpea. Chickpea grown at high PPD and narrow rows in Australia enhanced WU and seed yield, outweighing increased water depletion (Leach and Beech, 1988; Beech and Leach, 1989).

Response of different pea leaf types to high and low moisture stress showed significant differences in WU at high moisture stress but no differences when moisture was not limiting (Alvino and Leone, 1993). Li et al. (2006) reported higher CGR for fern-leafed cultivars than unifoliolate-leafed cultivars but no PPD effect in a study of kabuli chickpea cultivars in the Brown Soil and Dark Brown Soil zones of the Canadian Prairies. Richards (1991) proposed genetic improvement of WUE through an increase in T relative to E_s by selecting for prostrate growth habit or higher biomass in temperate crops such as wheat. In Syria, prostrate-spreading chickpea increased WUE compared to erect forms, although growth habit and phenology were confounded (ICARDA, 1982).

Information on the effect of varying chickpea canopy types on early crop development, WU and WUE on the Canadian Prairies is generally lacking. Canopy traits such as leaf type and growth habit together with PPD which contribute to early and/or greater canopy development may decrease soil evaporation and thus increase the fraction of soil moisture available to the crop for transpiration and thus increase biomass production, seed yield and WUE of chickpea on the Canadian Prairies.

2.7 Crop Growth Rate, Biomass Accumulation and Harvest Index in Chickpea

Seed yield production in crops is a function of seasonal accumulated biomass and the subsequent partitioning of the biomass to seed yield. Donald (1962) termed the conversion of biomass to seed yield as harvest index. An increase in biomass or HI or both, where the two factors are independent of each other, would increase seed yield potential. From both equation 2.1, i.e., Seed yield = WUE x WU x HI

(Passioura, 1977) and Sinclair's (1993) equation:

$$\text{Seed yield} = \text{RUE} \times \text{RI} \times \text{HI} \quad [2.3]$$

seed yield can be increased by increasing HI and/or biomass, where an increase in biomass contributes to an increase in WUE and RUE, since WUE and RUE are biomass per unit WU and radiation, respectively.

Seed yield improvements in grain crops over the past century have been largely attributed to increases in HI (Sinclair, 1998). For example, increases in seed yield of cereals such as wheat and barley have been shown to correspond to increases in HI (Austin et al., 1980; Riggs et al., 1981; Perry and D'Atuono, 1989; Boukerrou and Rasmusson, 1990). Donald and Hamblin (1976) recommended increasing both biomass and HI in cereal breeding for seed yield improvement.

In legumes, Hanlan et al. (2006) reported that highest yielding lentil genotypes produced the most biomass but did not always have the highest HI on the Canadian Prairies. Li et al. (2006) found kabuli chickpea cultivars with the highest seed yield had the highest HI but did not accumulate the most biomass. However, a number of studies on legumes have revealed that both biomass and HI are major contributors to seed yield in soybean (Kumudini et al., 2001), in chickpea (Singh et al., 1990; López-Bellido et al., 2004) and in lentil (Muehlbauer, 1996). Lentil germplasm showing high seed yield together with corresponding high biomass were reported at three locations in the Middle East (ICARDA, 1993) as well as at Pullman in the US (Muehlbauer, 1996). Muehlbauer (1996) therefore argued that seed yield improvement in legumes could be possible through increased biomass and not solely through increases in HI.

Donald et al. (1978) also defined seed yield as the product of crop CGR, duration of reproductive growth and the fraction of CGR partitioned to seed yield. In chickpea, both Williams and Saxena (1991) and Krishnamurthy et al. (1999) found CGR was the most important factor influencing seed yield production. The biomass accumulated by a crop at any point in time is a reflection of crop growth. Therefore, a high CGR, especially, early in the season may contribute to early vigor, rapid canopy closure and early maturity, all of which are highly desirable attributes in short-season production systems.

3.0 Optimizing Plant Density for Varying Chickpea (*Cicer arietinum* L.) Canopy Types in Short-Season Production Systems

3.1 INTRODUCTION

Chickpea (*Cicer arietinum* L.) is relatively new to the Canadian Prairies with commercial production commencing in the mid-nineteen nineties. Production of chickpea is concentrated in the Brown Soil and Dark Brown Soil zones of the Canadian Prairies and accounts for about 90% of the production. A major limitation to crop production on the Canadian Prairies is the shortness of the growing season from May to August, with the frost-free period generally less than 120 days. Crop yield is a function of radiation intercepted over the growing season, the efficiency of converting the intercepted radiation to biomass and the partitioning efficiency of biomass to seed yield (Sinclair, 1993). In time-constrained production systems, therefore, maximizing the limited solar radiation could lead to yield improvement. Factors affecting radiation interception include plant population density (PPD) and plant canopy elements such as leaf type (i.e., as defined by leaf shape), and overall plant shape or growth habit which subsequently influences canopy photosynthesis culminating in yield. Exploration of these factors regarding their contribution to seed yield under varying PPDs is the focus of this experiment.

Two leaf types (fern and unifoliate) and three growth habits (bushy, erect and spreading) are exhibited by chickpea cultivars grown on the Canadian Prairies. Leaf type and growth habit are each controlled by single Mendelian genes (Muehlbauer and Singh, 1987). The pinnately compound fern leaves are expected to have better seasonal radiation capture by allowing deeper penetration of radiation into the canopy than the simple unifoliate leaves. The more branched bushy and spreading growth habits may have earlier and greater canopy closure than the erect growth habit. This may result in differences in PPD required for maximum yield by the contrasting leaf types and growth habits.

Hughes et al. (1987) reported greater solar radiation interception at higher PPD than at lower PPD but radiation interception between erect and spreading growth habits was similar in chickpea. However, the study did not report on the effects of PPD and growth habit on yield. In pea (*Pisum sativum* L.), a higher PPD is required by leafless cultivars than either semi-leafless or conventional types (Heath and Hebblethwaite, 1987). The higher PPD of the leafless cultivars allows production of a canopy size which is adequate for maximum radiation interception and high yields. However, Heath et al. (1991) found no differences in optimum densities for semi-leafless and leafed peas.

Plant population density is the most flexible agronomic management tool and can be controlled by the producer depending on the seeding date, seeding conditions and the expected canopy growth. In addition, high PPD does not negatively influence yield in good years if disease resistant genotypes are used or disease is controlled (Cooper, 1989). Traditionally, the lowest PPD for maximal yield in a production zone is chosen, but for short-season production, higher PPDs may be required as shown in short-season soybean (*Glycine max* L. Merr) production systems (Ball et al., 2000). This is because under conditions of cool temperature, inadequate moisture or late seeding, the development of the crop's leaf area is slower or limited, thus leading to lower biomass and lower yield potential.

Rapid leaf development can be increased by higher PPD. A crop that is able to generate leaves as early in the season as possible provides the most effective radiation capture throughout the season (Ball et al., 2000) particularly when the season length is less than 120 days. Westgate et al. (1997) indicated that higher PPD may lead to greater maize yield due to early canopy closure in the short growing season of the Northern Corn Belt. Limitations to canopy development may affect yield more significantly than variations in leaf photosynthetic rate (Gifford and Evans, 1981).

The fungal disease ascochyta blight caused by *Ascochyta rabiei* (Pass.) Labrousse is of major concern to chickpea production in Canada because no highly resistant cultivars are presently available. The canopy microclimate important for radiation interception and disease likelihood is influenced by temperature, relative humidity and indirect effects of canopy architecture. Varying

leaf type and growth habit at a range of PPDs may modify the canopy environment sufficiently to allow different levels of disease infection. Gan et al. (2003b; 2007) reported higher disease severity with unifoliate than fern leaves. No differences in disease severity with increasing PPD at three out of four growth stages were found by Gan et al. (2003b), but disease severity increased as PPD increased in some but not all cultivars of chickpea on the Canadian Prairies (Gan et al., 2007). Effect of chickpea growth habit on ascochyta blight is, however, unknown.

Plant height and height of lowest pod has been shown in various crops to increase with increasing PPD as a result of increased competition amongst plants (Weber et al., 1966; Hicks et al., 1969; Heath et al., 1991; Gan et al., 2003a; Edwards and Purcell, 2005). Height of the lowest pod is of particular importance as it improves mechanical harvesting of the chickpea crop by decreasing harvest losses. Akhter and Sneller (1996) found plant height and number of nodes on the main-stem in soybean to be associated with seed yield while Gan et al. (2006) reported number of nodes on the main-stem in chickpea differed in a dry year (20 nodes in 2001) from a wet year (24 nodes in 2002). Effect of PPD on number of nodes on main-stem in chickpea on the short-season Canadian Prairies is unknown.

Seed size in chickpea is important to market price, especially in the large-seeded kabuli seed class. Therefore, it is essential to investigate the response of seed size to high PPDs. Studies in the Brown Soil zone have found no correlation between seed weight with PPD in both kabuli and desi chickpea (Liu et al., 2003), and a negative impact of increasing PPD on the diameter of kabuli chickpea greater than 9 mm in three out of six location-years (Gan et al., 2003a). In the Mediterranean-type environment of south-western Australia, seed weight did not respond to PPD in most locations in two years but a decreasing trend was noted in all locations in a third year (Jettner et al., 1999).

The currently recommended PPD for chickpea production in Saskatchewan is 44 plants m^{-2} (Saskatchewan Pulse Growers, 2000). In a study involving a total of four cultivars, Gan et al. (2003a) determined the effect of a narrow range of PPDs (20 to 50 plants m^{-2}) on seed yield in the Brown Soil zone and tentatively set the optimum PPD at 40 to 45 plants m^{-2} for desi chickpea and 35 to 40 plants m^{-2} for both small and large-seeded kabuli chickpea. Information on optimum

PPD of chickpea for Saskatoon in the moister Dark Brown Soil zone is however lacking. With more cultivars developed by the Crop Development Center (CDC) in Saskatoon made available to farmers in the Northern Great Plains, the question of which PPD produces maximum seed yield warrants revision.

Seed yield in chickpea grown on wheat (*Triticum aestivum* L.) stubble showed either an asymptotic or parabolic response to PPD. Under summer fallow, however, seed yield increased with increasing PPD with no obvious optimum PPD, suggesting that moister conditions under summer fallow may be the underlying factor for the observed differences (Gan et al., 2003a). Differences in moisture as well as soil conditions of the Brown Soil and the Dark Brown Soil zones may therefore require different optimum PPDs for varying chickpea canopy types.

The objectives of this current experiment were to:

- (i) determine PPD for maximum seed yield of varying chickpea canopy types in Swift Current and Elrose in the Brown Soil production zone and Saskatoon in the Dark Brown Soil production zone of the Canadian Prairies by investigating seed yield responses to a wider range of PPDs (30 to 85 plants m⁻²),
- (ii) evaluate the effect of leaf type, growth habit and PPD on plant height, height to lowest pod, maximum node count, individual seed weight and disease severity in chickpea in short-season production systems of the Canadian Prairies.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Design

Experiments were conducted over eight location-years comprising three locations in 2002, two locations each in 2003 and 2004 and one location in 2005 (Table 3.1). The three locations in 2002 were the Agriculture and Agri-Food Canada Research Centre near Swift Current, SK (50° 16' N, 107° 47' W) and leased land at Elrose, SK, (51 ° 7' N 108 ° 6' W) both in the Brown Soil zone and the University of Saskatchewan Goodale Experimental Farm, near Saskatoon, SK (52° 7' N, 106° 37' W) in the Dark Brown Soil zone. In 2003 and 2004 the Swift Current and Saskatoon locations were seeded, but in 2005 only the Swift Current location was seeded. Results from Elrose were excluded from the analyses because of severe drought and grasshopper infestation in 2002. The soil type in Swift Current (Brown Soil zone) was an Orthic Brown Chernozem (Aridic Haploboroll) - Swinton silty loam while Saskatoon (Dark Brown Soil zone) comprised of a Dark Brown Chernozem (Typic Boroll) soil. In all years, the previous rotations were under chemical fallow in the drier Brown Soil zone (Swift Current) whereas the moister Dark Brown Soil zone (Saskatoon) were under wheat.

Eight cultivars consisting of five CDC cultivars (CDC Anna, CDC Cabri, CDC ChiChi, CDC Ebony and CDC Xena), two United States Department of Agriculture cultivars (Evans and Myles) and one cultivar (Amit, previously known as B-90) developed by the Agricultural Research Organization, Israel, with a range of leaf types and growth habits, were seeded in 2004 and 2005 (Table 3.2). Four cultivars were seeded in 2002 and seven cultivars were seeded in 2003 due to insufficient seed available for the other cultivars (Table 3.2). Resistance to ascochyta blight ranged from poor to fair for all cultivars, with the exception of CDC Xena and Evans which have very poor rating. Plots were over-seeded by 15% in order to achieve five target PPDs of 30, 45, 60, 75, 85 plants m⁻². For each location-year, the experimental design was a randomized complete block design with a factorial combination of cultivar and PPD and treatment combinations were replicated four times. Row spacing was maintained at 0.31 m for all seven location-years. Seeding date, plot size and number of rows were as presented in Table 3.1.

Table 3.1 Seeding date, plot size, number of rows and harvest date of chickpea cultivars over eight location-years in Swift Current in the Brown Soil zone (2002 to 2005) and Saskatoon in the Dark Brown Soil zone (2002 to 2004).

Year	Number of rows	Plot size (m)	Seeding date	Harvest date
<u>Swift Current (Brown Soil zone)</u>				
2002	6	1.8 x 4.9	14 May	Oct 23
2003	6	1.8 x 6.7	20 May	Aug 22
2004	6	1.8 x 10.0	14 May	Oct13
2005	6	1.8 x 4.9	9 May	Sep 2 ^z & Sep 10 ^y
<u>Elrose (Brown Soil zone)^x</u>				
2002	4	1.2 x 4.9	22-May	Oct 9
<u>Saskatoon (Dark Brown Soil zone)</u>				
2002	4	1.2 x 4.3	30 May	Sep 25
2003	8	2.4 x 3.7	14 May	Sep 1
2004	16	4.8 x 3.6	25 May	Nov 10

^z CDC Cabri and CDC Ebony

^y CDC Anna, Amit, CDC ChiChi, CDC Xena, Evans and Myles

^x Excluded from analysis due to severe drought effect

Table 3.2 Leaf type, growth habit and seed class of chickpea cultivars grown over eight location-years in Swift Current in the Brown Soil zone (2002 to 2005) and Saskatoon in the Dark Brown Soil zone (2002 to 2004).

Cultivar ^z	Leaf type	Growth habit	Seed class
CDC Xena ^{y,x}	Unifoliate	Erect	Kabuli
Evans ^{y,x}	Unifoliate	Erect	Kabuli
Amit ^{y,x}	Fern	Erect	Kabuli
Myles ^{y,x}	Fern	Erect	Desi
CDC Anna	Fern	Bushy	Desi
CDC Cabri ^x	Fern	Bushy	Desi
CDC ChiChi ^x	Fern	Bushy	Kabuli
CDC Ebony ^x	Fern	Spreading	Desi

^z All eight cultivars were seeded in 2004 and 2005

^y Four cultivars grown in 2002

^x Seven cultivars grown in 2003

A mixture of carbathiin and thiabendazole (Crown) at 600 ml 100 kg⁻¹ seed and metalaxyl (Apron) at 16 ml 100 kg⁻¹ seed was used for pre-seed treatment against seed-borne diseases. Seeding depth was 0.05 m in all location-years and seeds were inoculated with 5.5 kg ha⁻¹ of granular *Rhizobium* inoculant, Nodulator® (Becker Underwood Inc, Saskatoon, SK) within the seed row at seeding. Ascochyta blight was controlled in Swift Current (Brown Soil zone) by four fungicide applications, including two applications each of pyraclostrobin (Headline) at 0.40 L ha⁻¹ and chlorothalonil (Bravo) at 4.0 L ha⁻¹. In Saskatoon (Dark Brown Soil zone), the fungicides Bravo at 3.20 L ha⁻¹ was applied at first flower, followed by two applications of Headline at 0.40 L ha⁻¹ at 10-day intervals.

Weeds were controlled in Swift Current (Brown Soil zone) using a pre-seeding application of ethalfluralin (Granular Edge) at 17.0 kg ha⁻¹, a pre-emergence application of glyphosate (Roundup) at 2.50 L ha⁻¹ and imazethapyr (Pursuit) at 0.03 L ha⁻¹ and a post-emergence application of sethoxydim (Poast Ultra) at 0.48 L ha⁻¹. In Saskatoon (Dark Brown Soil zone) control of weeds involved spring application of Granular Edge at 28.0 kg ha⁻¹ and pre-emergence application of the herbicide Pursuit at 0.07 L ha⁻¹. Grasshopper incidence was controlled in Swift Current by spraying deltamethrin (Decis) at 119.0 ml ha⁻¹ at flowering in 2002 and dimethoate (Cygon) at first flower at 0.50 L ha⁻¹ in 2003 while in Saskatoon, chlorpyrifos (Lorsban) was sprayed at early flowering and mid-pod fill at 1.0 L ha⁻¹ in 2002, 2003 and 2004.

3.2.2 Data Collection and Calculations

Stand counts were conducted at about the 4-node stage from two or three randomly selected 1-m sections of two or three different rows per plot. From about the 6-node stage until physiological maturity, number of nodes on main-stem was noted for three plants per plot at about 7- to 14-day intervals in both locations from 2003 to 2005. At harvest maturity, plant height and height to lowest pod were also measured in both locations from 2003 to 2005. Plots were combined at harvest maturity and the seed air-dried at 40 °C for seven days in order to obtain seed yield. In Swift Current individual seed weight and disease data were also obtained from 2002 to 2005. Individual seed weight was determined based on two sub-samples of 500 seeds per plot. The Horsfall-Barratt scale was used for disease grading at early flowering and late podding growth stages of 5 random plants per plot (Horsfall and Barratt, 1945). The grading scale was from 0 to

11, with 0 and 11 representing no disease and completely diseased, respectively. The grading scale was then converted to mean percentage leaf area with a range of 1.2 to 98.6%.

Weather data (mean air temperature and rainfall) were logged daily using automated weather stations in both Swift Current and Saskatoon, except for Saskatoon in 2002 where environmental data were obtained from University of Saskatchewan Weather Station at Kernen Farm Research Station (Table 3.3), less than 25 km from the plots.

3.2.3 Statistical Analysis

All statistical analyses were performed using SAS version 9.0 (SAS Institute, 1999 Cary, NC, USA). For all variables, outliers were detected based on cultivar–target PPD combinations for Student’s Residual regressions and values greater than 2.0 or less than -2.0 were removed from the analyses (Appendix 1). Data were analyzed for each location-year separately because actual PPD varied over locations and years (Table 3.4), and treatment effects were significantly different across years for each location (soil zone).

Response of seed yield (g m^{-2}) to actual PPD (plants m^{-2}) was modeled by the linear function

$$\ln(\text{yield plant}^{-1}) = a + (b \times \text{PPD}) \quad [3.1]$$

where a is the ordinate intercept and b is the negative slope of the regression line. The PPD that produces the maximum seed yield per unit area (maximum yield PPD) was estimated as $-1/b$ while maximum seed yield was also estimated as

$$e^{(a-1)} \times \text{maximum yield PPD} \quad [3.2]$$

(Duncan, 1958; Tollenaar, 1989; Tollenaar, 1992; Tokatlidis, 2001). Data were fitted using Equation 3.1 as it gave the highest adjusted R^2 values compared with fitting linear and quadratic curves to seed yield (g m^{-2}) by actual PPD regression plots. Treatments of leaf types, growth habits and seed classes were tested against each other for seed yield differences at PPDs of 10 to 100 at 10 unit increments, using contrast statements.

Regressions were performed using the PROC REG procedure. Analysis of variance (ANOVA) of maximum node number, final plant height, lowest pod height, disease severity and individual seed weight were also performed using the PROC MIXED procedure for leaf type and growth habit with replicate as random effect and cultivar and PPD as fixed effects. The default modified Tukey's statistic of the PROC MIXED procedure was used for mean separation at $P < 0.05$ and mean separation output were then converted to letter groupings (Saxton, 1998). Not all combinations of canopy traits (leaf type x growth habit) were possible, so contrast statements were used to separate means for leaf types and growth habits. The unifoliate versus fern leaf contrast compared CDC Xena and Evans (unifoliate) against Amit, Myles, CDC Anna, CDC Cabri, CDC ChiChi and CDC Ebony (fern). The bushy, erect and spreading growth habits contrast compared CDC Anna, CDC Cabri and CDC ChiChi (bushy), CDC Xena, Evans, Amit and Myles (Erect) and CDC Ebony (Spreading). The erect growth habit was confounded with leaf type but all the bushy and spreading cultivars had fern leaves. Actual PPD was also used to test for a linear and quadratic response of variables.

3.3 RESULTS

3.3.1 Weather Effects

Seasonal (May to September) weather conditions experienced during the experiments reflected the variability of the weather on the Canadian Prairies. The pattern of variation in the weather was similar in both locations (Table 3.3). Three years (2002, 2004 and 2005) were wetter and cooler than the long-term average while 2003 was dry and hot and, consequently, a short season. Seasonal rainfall in Swift Current in 2002, 2004 and 2005 were above the long-term average by 69, 30 and 13% respectively while in Saskatoon, rainfall was above the average by 16 and 28% in 2002 and 2004, respectively. In 2003, seasonal rainfall in both locations was below the long-term average by 22%. With the exception of 2004 (both locations) and 2003 in the Swift Current, total monthly rainfall in May was at most about half the long-term value. In 2003, seasonal total monthly rainfall in July in the Swift Current and June in Saskatoon was also less than 50% of the long term average.

Late season rains in August, typical of the Prairie production zones, enhanced the indeterminate growth habit of chickpea and resulted in late harvests evident in all location-years with the exception of both locations in the drought year of 2003. In all the wet years (2002, 2004 and 2005) in both locations, August rainfall was higher than the long term average and was particularly so in 2004 when August rains exceeded the long-term average by 160 and 135% in the Swift Current and Saskatoon, respectively. The seasonal weather in Saskatoon in 2004 was quite challenging because of an early frost on August 20 and 24 cm of snow in October, resulting in much lower yields in Saskatoon than in Swift Current (Figs 3.1, 3.2 and 3.3).

Seasonal mean monthly temperatures were slightly below the long-term average in 2002 and 2005, i.e., 4 and 3% for Swift Current and Saskatoon, respectively, in 2002 and 3% in the Saskatoon in 2005. Seasonal mean monthly temperatures were much cooler in 2004, i.e., 11 and 12% in Swift Current and Saskatoon, respectively. In 2003, however, mean seasonal temperature was 4 and 3% above the long-term average in Swift Current and Saskatoon, respectively.

Table 3.3 Total monthly rainfall (mm) and mean monthly air temperature (°C) in Swift Current (2002 to 2005) and Saskatoon (2002 to 2004).

	Swift Current (Brown Soil zone)				Long term ^z	Saskatoon (Dark Brown Soil zone)			
	2002	2003	2004	2005		2002 ^y	2003	2004	Long term ^z
	<u>Rainfall (mm)</u>								
May	11	42	72	22	44	2	14	36	42
June	143	79	66	123	66	62	31	87	63
July	73	8	61	21	52	67	64	75	58
Aug	102	21	72	52	40	87	31	73	37
Sept	59	30	27	41	28	49	39	25	30
Total	390	180	299	259	230	267	179	296	230
	<u>Mean temperature (°C)</u>								
May	9	11	8	10	11	8	12	8	12
June	16	15	13	15	16	17	16	13	16
July	20	20	18	19	18	20	18	18	19
Aug	16	22	15	17	18	16	21	15	17
Sept	12	12	12	13	12	12	11	12	11
Mean	14	16	13	14	15	15	16	13	15

^z Long term (1970 – 2000) average for Saskatoon from Environment Canada (2006)
(http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html)

^y University of Saskatchewan Weather Station at Kernen Farm Research Station

3.3.2. Actual Plant Population Density

Stand counts showed that actual PPD varied amongst location-years and in each location-year, actual PPD increased significantly with increasing target PPD with the exception of the 75 and 85 target PPDs in Swift Current in 2002 and 2003 (Table 3.4). Percentage of actual PPD to target PPD decreased with increasing target PPD (Table 3.5). At the lowest target PPD of 30 plants m⁻², 100% of target PPD was achieved in two location years (Saskatoon in 2002 and Swift Current in 2005) and the lowest was 83%. However, at the highest target PPD of 85 plants m⁻², the highest and lowest percentages of actual to target PPD were 87% (Saskatoon in 2002) and 69% (Swift Current in 2002), respectively.

Low total rainfall in May together with low temperatures around seeding may have contributed to low emergence and hence low stands observed in this research. Total rainfall in May was generally low with total May rainfall being at most 50% of the long-term average in four out of the seven location-years (Table 3.3). Mean daily temperatures in May, with the exception of 2003 were also cooler than the long-term average.

In 2002, crop stand averaged over all PPDs was 20% higher in Saskatoon than in Swift Current (Table 3.4). This difference in crop stand could be attributed to dry seed bed conditions in Swift Current due to the extreme drought of the preceding year (2001). However, late seeding on May 30 in Saskatoon which coincided with rains in June may have allowed more seed to successfully germinate and become established. Crop stand between locations in 2003 and 2004 were however, comparable, i.e., crop stand in 2003 was 8% higher in Swift Current than in Saskatoon while in 2004 crop stand was 6% higher in Saskatoon than in Swift Current.

3.3.3 Plant Population Density Effects on Seed Yield

The ln linear seed yield per plant – actual PPD function (Equation 3.1) fitted well in all location-years with $R^2 \geq 0.80$ and all slope coefficients significant at $P < 0.05$. To illustrate the effect of actual PPD on seed yield m⁻², the linear function was converted to a seed yield per unit area by PPD plot i.e.

$$Y = e^{(a + b \times \text{PPD})} \times \text{PPD} \quad (3.3)$$

where Y is seed yield per unit area in g m⁻², the product of yield plant⁻¹ and PPD (Duncan, 1958).

Table 3.4 Target and actual plant population density of chickpea cultivars over seven location-years in Swift Current (SC) from 2002 to 2005 and Saskatoon (STN) from 2002 to 2004.

Target (plants m ⁻²)	Actual plant population density (plants m ⁻²)						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
30	25d ^z	30e	27d	26e	26e	29e	30e
45	36c	43d	41c	37d	38d	40d	43d
60	45b	52c	54b	50c	48c	52c	52c
75	54a	63b	65a	59b	56b	61b	59b
85	59a	74a	70a	66a	65a	66a	65a

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

Table 3.5 Percent of actual to target plant population density of chickpea cultivars over seven location-years in Swift Current (SC) from 2002 to 2005 and Saskatoon (STN) from 2002 to 2004.

Target (plants m ⁻²)	Percent of actual to target plant population density (%)						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
30	83 ^z	100	90	87	87	97	100
45	80	96	91	82	84	89	96
60	75	87	90	83	80	87	87
75	72	84	87	79	75	81	79
85	69	87	82	78	76	78	76

^z For example, 83% of the target 30 plants m⁻² were established in Swift Current in 2002

Treatment effects regarding the general response of seed yield m^{-2} to PPD were quite consistent for both locations in any given year (Figs 3.1, 3.2 and 3.3). As PPD increased, seed yield increased in a curvilinear fashion. The increase in seed yield m^{-2} either approached a maximum, or reached a maximum and either remained constant or began to drop (Figs 3.1, 3.2 and 3.3). For each year, seed yield was higher in Swift Current than in Saskatoon except in 2003 where seed yield in Saskatoon was slightly higher than seed yield in Swift Current. Least difference in seed yield between the two locations was noted in 2003 which was the driest year. Minimum treatment differences for each location-year were also recorded in the dry year of 2003.

3.3.3.1 Plant Population Density Effects on Seed Yield for Leaf Types

The PPD at which maximum yield was produced (maximum yield PPD), was higher for unifoliolate-leaved cultivars than fern-leaved cultivars in four out of seven location-years (Fig 3.1). In Saskatoon in 2002, the maximum yield PPD for both leaf types were the same at 73 plants m^{-2} whereas in both locations in 2003, it was lower for the unifoliolate cultivars than the fern cultivars. Amongst years in a given location, maximum yield PPD tended to be higher for the unifoliolate cultivars than the fern cultivars in Swift Current but was mixed in Saskatoon. In Swift Current maximum yield PPD was higher for the unifoliolate cultivars than the fern cultivars by 32%, 30% and 8% in 2002, 2004 and 2005, respectively, while maximum yield PPD was lower for the unifoliolate cultivars than the fern cultivars by 7% in 2003. In Saskatoon both leaf types had the same maximum yield PPD in 2002 while maximum yield PPD was lower for the unifoliolate cultivars by 7% in 2003 and higher for the unifoliolate cultivars by 17% in 2004. Between locations for a given year, maximum yield PPD was lower for the unifoliolate cultivars than the fern cultivars in 2003 while the reverse response was observed in 2004. In 2002, however, both leaf types had the same maximum yield PPD in Saskatoon whereas the unifoliolate cultivars had a higher maximum yield PPD than the fern cultivars in Swift Current.

Cultivars with fern leaves produced significantly higher yields than cultivars with unifoliolate leaves at all tested PPDs (i.e., 10, 20, 30 to 100 plants m^{-2}) in all location-years except in Swift Current in 2003 at the 10 and 20 plants m^{-2} PPDs where differences were not significant between the two leaf types (Figs. 3.1).

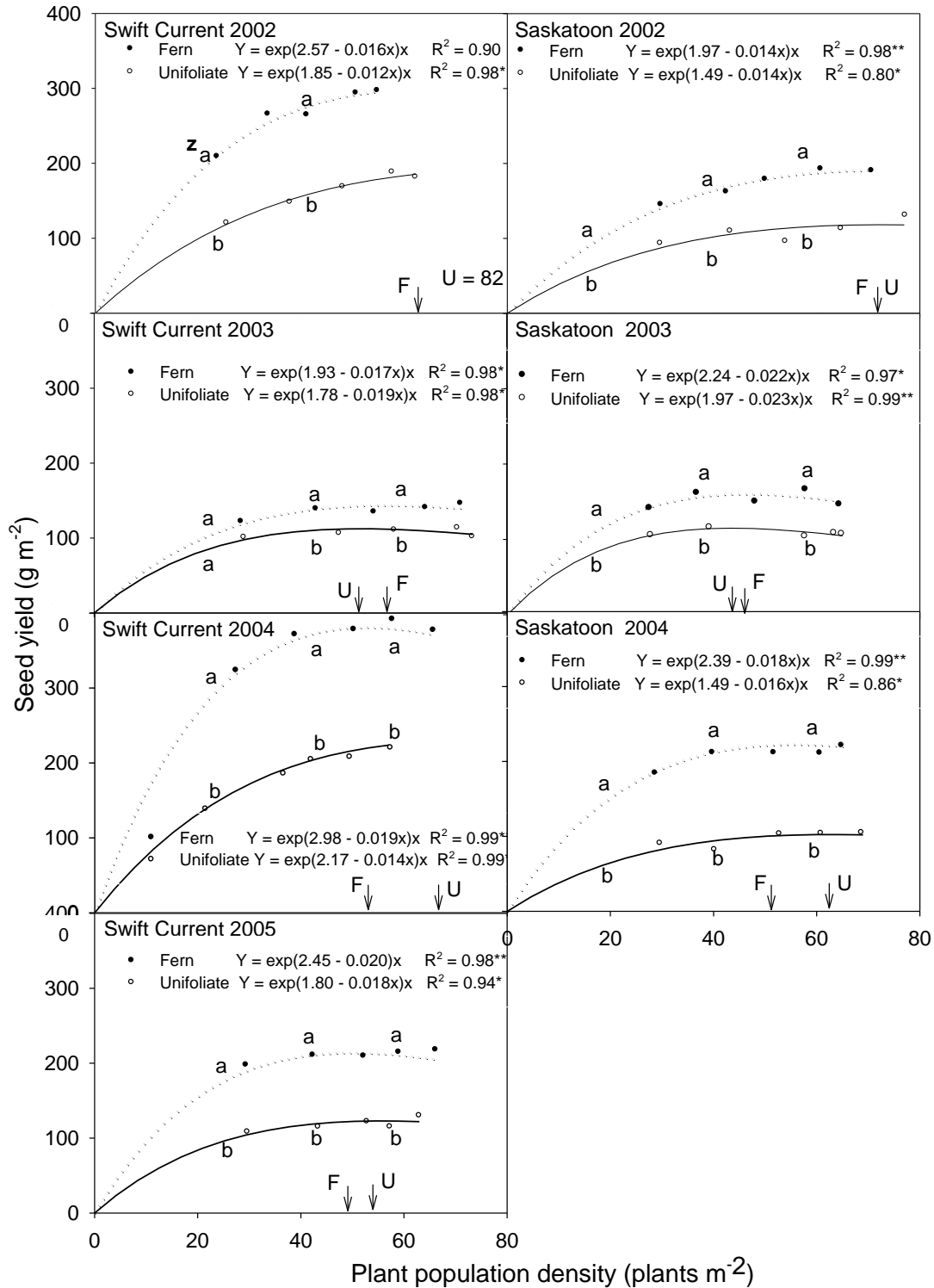


Fig. 3.1 Response of chickpea seed yield to actual plant population density (PPD) of fern (F) and unifoliate (U) leaf types in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004 showing fitted curves (lines) of treatment means (data points). ^z Means at 20, 40 and 60 PPD with same letter are not significantly different at P < 0.05. Arrows represent PPD at maximum yield.

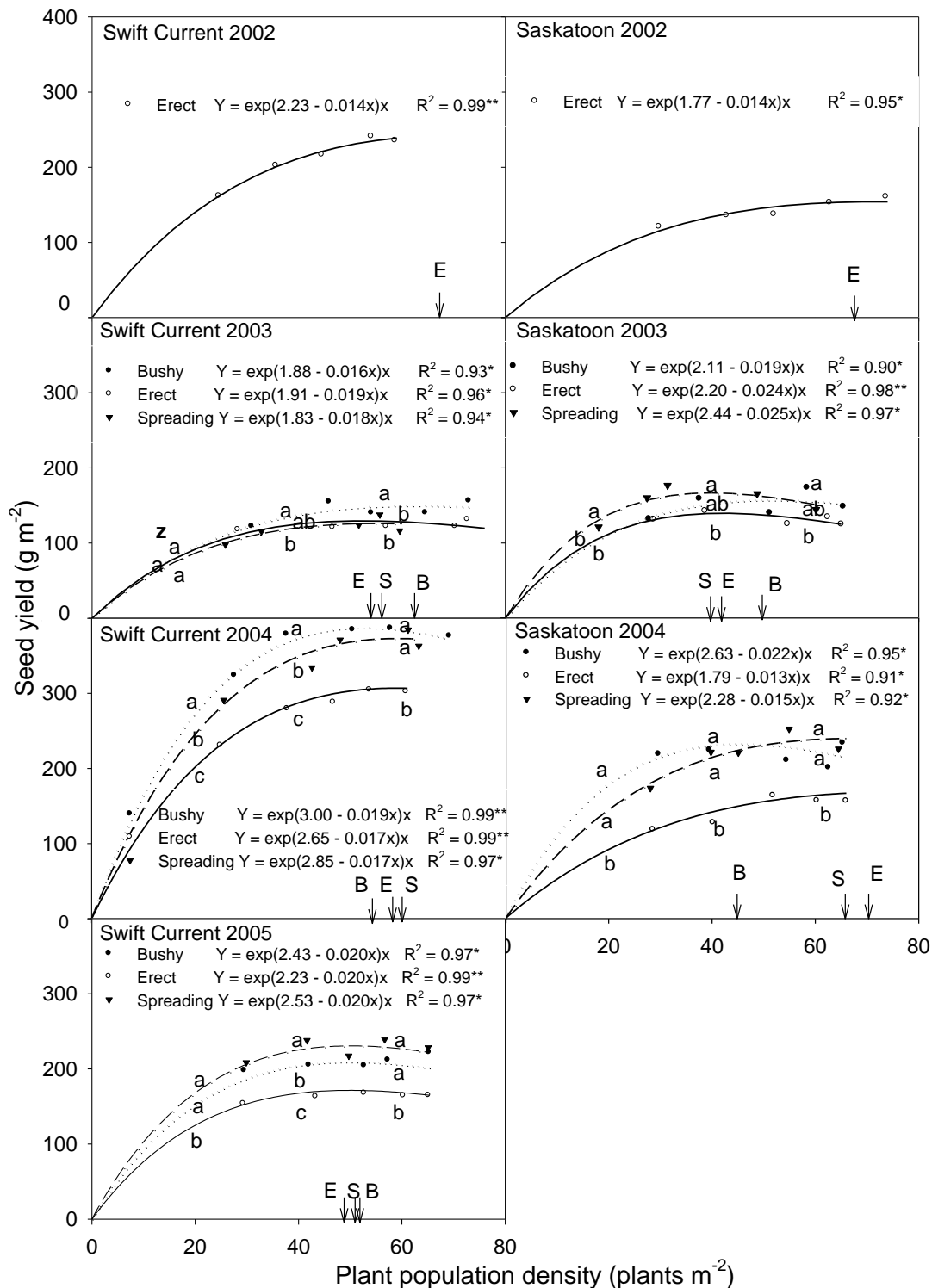


Fig. 3.2 Response of chickpea seed yield to actual plant population density (PPD) of bushy (B), erect (E) and spreading (S) growth habits in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004 showing fitted curves (lines) of treatment means (data points).

^z Means at 20, 40 and 60 PPD with same letter are not significantly different at P < 0.05. Arrows represent PPD at maximum yield.

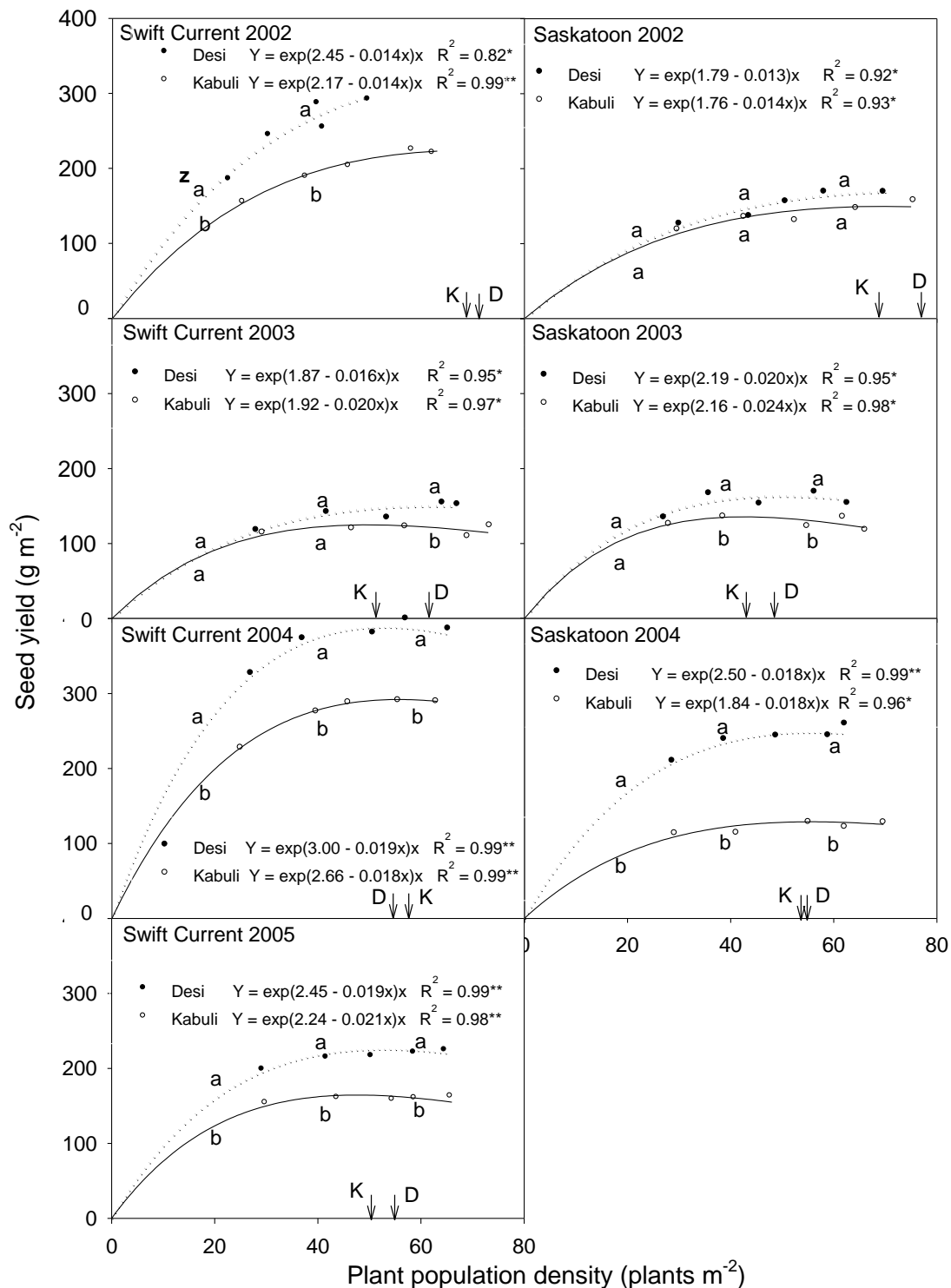


Fig. 3.3 Response of chickpea seed yield to actual plant population density (PPD) of desi (D) and kabuli (K) seed classes in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004 showing fitted curves (lines) of treatment means (data points). ^z Means at 20, 40 and 60 PPD with same letter are not significantly different at $P < 0.05$. Arrows represent PPD at maximum yield.

3.3.3.2 Plant Population Density Effects on Seed Yield for Growth Habits

The maximum yield PPD for growth habits did not show a distinct pattern either amongst years or between the two locations (Fig 3.2). Amongst years in a given location, the maximum yield PPD was highest for the bushy cultivars in 2003, lowest for the bushy cultivars in 2004 and similar across three growth habits in 2005 (52, 49 and 51 for bushy, erect and spreading growth habits, respectively). Between locations the maximum yield PPD attained for the erect cultivars was the same in 2002 (71 plants m⁻²), but was higher in Swift Current by 24% in 2003 and lower in Swift Current by 21% in 2004.

The bushy and spreading cultivars generally did not differ significantly in seed yield but produced significantly higher seed yields than the erect cultivars (Fig 3.2). Minimal differences in seed yield were observed amongst the three growth habits in response to varying PPD in the dry year of 2003. For example, no significant difference between erect and spreading habits in Swift Current was noted and the only significant difference was at 20 plants m⁻² in Saskatoon (Fig 3.2).

3.3.3.3 Plant Population Density Effects on Seed Yield for Seed Classes (Desi vs. Kabuli)

The PPD at which the maximum seed yield was produced tended to be higher for desi than for kabuli chickpea both amongst years of a given location and also between locations of a given year. Maximum yield PPD was higher for desi chickpea than kabuli chickpea in six out of seven location-years except for Saskatoon in 2004 where the maximum yield PPD was 5% higher for kabuli chickpea than for desi chickpea (Fig 3.3).

In three out of seven location-years desi chickpea yielded significantly higher than kabuli chickpea at all tested PPDs (Fig 3.3). In Swift Current in 2002, seed yield was significantly higher for desi than kabuli chickpea at all tested PPDs except at 100 plants m⁻². There were, however, no significant differences between desi and kabuli chickpea in Saskatoon in 2002 and also at PPDs 10, 20, 30 and 40 plants m⁻² in Swift Current and 10, 20, 30, and 100 plants m⁻² in Saskatoon in 2003. Otherwise, seed yield was significantly higher for desi than kabuli chickpea.

3.3.4 Maximum Node Count on Main-Stem

Over five location-years, fern-leafed cultivars had a significantly higher maximum node number on the main-stem than cultivars with unifoliate leaves (Table 3.6). Regarding growth habit, maximum node number did not differ significantly in three out of five location-years. The spreading cultivar had a significantly higher maximum node number in the other two location-years but the response of the bushy and erect cultivars was inconsistent. The much branched bushy cultivars produced significantly higher maximum node numbers than the less branched erect cultivars in only one out of five location-years. Maximum node count decreased significantly with increasing PPD in three location-years (Swift Current in 2003 and 2004 and Saskatoon in 2004) but was constant in two location-years (Swift Current in 2004 and 2005).

In both 2003 and 2004 maximum node number on the main-stem was greater for Saskatoon than Swift Current, indicating more growth in Saskatoon in the moister Dark Brown Soil zone. Gan et al. (2006) reported 20 nodes per main stem in the dry year of 2001 compared to the wetter year of 2002 which produced 24 nodes. In the dry year, 2003, the maximum number of nodes produced in Swift Current was similar to that produced in the wet year of 2004 and slightly lower than that of the other wet year of 2005. The higher maximum node number recorded in this research may be due to the fact that 2003 was not as dry as 2001 (Gan et al., 2006), with 2003 having 30 mm more rainfall (May to August) than 2001. The unifoliate cultivars had the lowest maximum node number of 22 in Swift Current in 2003 and 2004. A maximum node number of 26 was recorded for the 30 plants m⁻² PPD in Saskatoon in 2004.

Table 3.6 Effect of leaf type, growth habit and plant population density of chickpea cultivars on maximum node number on the main-stem over five location-years in Swift Current (SC) from 2002 to 2005 and Saskatoon (STN) from 2002 to 2004.

	Maximum node number on main-stem				
	2003		2004		2005
	SC	STN	SC	STN	SC
<u>Leaf type</u>					
Fern	24a ^z	26a	24a	26a	25a
Unifoliate	22b	24b	22b	24b	23b
<u>Growth habit</u>					
Bushy	24b	25b	24a	26a	25a
Erect	23c	25a	23a	26a	24a
Spreading	25a	25a	23a	25a	25a
<u>Target (plants m⁻²)</u>					
30	24 †	26 †	24	26 ‡	25
45	24	25	24	26	25
60	23	25	24	26	24
75	23	25	23	25	24
85	23	25	23	25	25

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

3.3.5 Plant Height and Lowest Pod Height

As expected, the spreading cultivars were significantly shorter (0.26 to 0.45 m) than the bushy (0.34 to 0.55 m) and erect (0.33 to 0.56 m) cultivars in all location-years (Table 3.7). Cultivars with bushy and erect growth habits had similar heights. No significant differences were observed in plant height at maturity between leaf types in three out of five location-years but the unifoliolate cultivars were significantly taller than the fern cultivars in two location-years. Plant height at maturity decreased with increasing PPD in four out of five location-years but no significant differences were observed in one location-year. Plants were much shorter in 2003, ranging from 0.26 to 0.35 m, which was an obvious result of moisture stress. In the other years, plant height ranged from 0.45 to 0.58 m.

Lowest pod height was significantly higher for unifoliolate-leaved cultivars than for fern-leaved cultivars in all five location-years i.e., 0.20 to 0.31 m vs. 0.15 to 0.24 m, respectively (Table 3.8). Lowest pod height was also significantly higher in cultivars with erect growth habit (0.18 to 0.27 m) followed by cultivars with bushy habit (0.16 to 0.24 m) and the spreading cultivar (0.12 to 0.22 m). In Saskatoon in 2004, however, there was no significant difference between the bushy and spreading cultivars. Lowest pod height increased significantly with increasing PPD in all but one location-year, with increase in lowest pod height ranging from 0.02 to 0.03 m (Table 3.8).

3.3.6 Disease Severity

Disease severity data for Swift Current showed that treatment responses to ascochyta blight, both the pattern and magnitude, were quite similar at the early flowering and late podding growth stages in all four years except in 2003 where a marked increase in the disease was noted at the late podding stage (Table 3.9). The worst year of ascochyta severity was noted in 2005, presumably because weather conditions were ideal for the fungal disease, i.e., not as wet as in 2002 and 2004 and not as cool as in 2004. The frequency of early season fungicide treatments may also have been insufficient resulting in the high ascochyta severity noted.

Table 3.7 Effect of leaf type, growth habit and plant population density of chickpea cultivars on plant height (m) at maturity over five location-years in Swift Current (SC) from 2002 to 2005 and Saskatoon (STN) from 2002 to 2004.

	Plant height (m)				
	2003		2004		2005
	SC	STN	SC	STN	SC
<u>Leaf type</u>					
Fern	0.32b ^z	0.33a	0.50b	0.54a	0.52a
Unifoliolate	0.34a	0.33a	0.55a	0.55a	0.52a
<u>Growth habit</u>					
Bushy	0.34a	0.34a	0.51a	0.55a	0.53a
Erect	0.34a	0.33a	0.52a	0.56a	0.53a
Spreading	0.26b	0.32b	0.45b	0.45b	0.45b
<u>Target (plants m⁻²)</u>					
30	0.32	0.35 †	0.53 †	0.58 †	0.51 †
45	0.33	0.34	0.53	0.54	0.52
60	0.32	0.33	0.51	0.51	0.52
75	0.32	0.32	0.50	0.55	0.52
85	0.33	0.31	0.48	0.52	0.51

^z Treatment means within a column followed by the same letter are not significantly different at P < 0.05 (Tukey's test).

† Actual plant population density showed a significant linear response (P < 0.05)

‡ Actual plant population density showed a significant quadratic response (P < 0.05)

Table 3.8 Effect of leaf type, growth habit and plant population density of chickpea cultivars on lowest pod height (m) at harvest maturity over five location-years in Swift Current (SC) from 2002 to 2005 and Saskatoon (STN) from 2002 to 2004.

	Lowest pod height (m)				
	2003		2004		2005
	SC	STN	SC	STN	SC
<u>Leaf type</u>					
Fern	0.16b ^z	0.15b	0.21b	0.23b	0.24b
Unifoliolate	0.20a	0.20a	0.27a	0.31a	0.28a
<u>Growth habit</u>					
Bushy	0.16b	0.16b	0.21b	0.23b	0.24b
Erect	0.18a	0.18a	0.24a	0.27a	0.27a
Spreading	0.13c	0.12c	0.18c	0.22b	0.18c
<u>Target (plants m⁻²)</u>					
30	0.16 †	0.16 †	0.21 †‡	0.23	0.23 †
45	0.16	0.16	0.23	0.26	0.25
60	0.17	0.17	0.23	0.24	0.25
75	0.17	0.18	0.23	0.26	0.26
85	0.18	0.18	0.23	0.26	0.26

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

Table 3.9 Effect of leaf type, growth habit and plant population density of chickpea cultivars on ascochyta blight severity (percent Horsfall-Barratt scale) in Swift Current from 2002 to 2005.

	Ascochyta blight (%)							
	2002		2003		2004		2005	
	Early flower	Late pod	Early flower	Late pod	Early flower	Late pod	Early flower	Late pod
<u>Leaf type</u>								
Fern	3b ^z	3b	6b	23b	6b	7b	24b	27b
Unifoliate	20a	12a	25a	33a	22a	15a	74a	77a
<u>Growth habit</u>								
Bushy			7b	22b	8b	8b	33b	36b
Erect	11	7	15a	25b	13a	10a	46a	49a
Spreading			3c	36a	4c	5c	5c	6c
<u>Target (plants m⁻²)</u>								
30	12	8	11 ‡	22 †	8 †	9	37	39
45	13	9	11	24	9	9	39	38
60	12	7	12	26	10	8	37	40
75	9	7	11	30	12	9	38	41
85	12	7	11	31	12	10	33	41

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

Percentage ascochyta blight severity was significantly higher in cultivars with unifoliate leaves (12 to 77%) than fern cultivars (3 to 27%) in all growth stage-years. Regarding growth habit, ascochyta blight severity increased significantly in the order of spreading, bushy and erect growth habit in all but one growth stage-year, the late podding stage in 2003, where disease severity was significantly higher in the spreading cultivar than in both the bushy and erect cultivars. Percentage ascochyta blight severity ranged from 3 to 36% in the spreading cultivar, 7 to 36% in the bushy cultivars and 7 to 49% in the erect cultivars. Increasing PPD generally did not affect ascochyta blight severity with no significant differences at five of the eight growth stage-years.

3.3.7 Individual Seed Weight

Individual seed weight was determined for Swift Current from 2002 to 2005. Individual seed weight generally increased with increasing PPD except in 2005 where a significant decrease in seed weight with increasing PPD was observed (Table 3.10). Individual seed weight ranged from 256 to 311 mg at the lowest target PPD of 30 plants m⁻² while at the highest target PPD of 85 plants m⁻² the seed weight ranged from 275 to 355 mg.

Table 3.10 Effect of plant population density of chickpea cultivars on individual seed weight (g) in Swift Current from 2002 to 2005.

Target (plants m ⁻²)	Individual seed weight (mg)			
	2002	2003	2004	2005
30	311 †	297 †	256 †‡	292 †
45	321	302	263	287
60	337	303	272	284
75	339	301	273	282
85	335	303	275	281

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

3.4 DISCUSSION

3.4.1 Optimum Plant Population Density

The PPD at which the highest seed yield was obtained, was averaged over years for each location (soil zone) for each treatment in order to ascertain the long term effect of an increase in chickpea PPD on seed yield on the Canadian Prairies (Table 3.11). Maximum yield PPD ranging from 53 to 65 plants m^{-2} increased seed yield by 23 to 49% above the seed yield achieved from the currently recommended PPD of 44 plants m^{-2} for all treatments responses except for the bushy and spreading growth habits in Saskatoon which had 0 and 9% maximum yield PPD above the recommended PPD, respectively. Eight out of 12 treatment responses had maximum yield PPD within the range of 53 to 58 plants m^{-2} . Moreover, where maximum yield PPD was at least 55 plants m^{-2} , the seed yield advantage of maximum yield PPD above the recommended PPD was 23% or greater. The highest average seed yield advantage of 49% yield increase over the recommended PPD was observed for the unifoliolate leaf cultivars in Swift Current at a PPD of 65 plants m^{-2} .

This research therefore suggests that an optimum PPD of 55 plants m^{-2} for both locations would result in at least a 23% increase in chickpea seed yield on the Canadian Prairies. Liu et al. (2003) reported a 20%, 27% and 17% seed yield increase for desi, small-seeded kabuli and large-seeded kabuli chickpea, respectively, as PPD increased from 20 to 50 plants m^{-2} on the Canadian Prairies. Saccardo and Calcagno (1990) recommended PPDs of 24, 40 and 80 plants m^{-2} for semi-prostrate, semi-erect and erect chickpea lines at 0.40, 0.25 and 0.12 inter-row spacing, respectively, and 0.10 m intra-row spacing under the Mediterranean conditions of Italy. In South-Western Australia, Jettner et al. (1999) suggested an optimum PPD of 50 plants m^{-2} for most chickpea crops and more than 70 plants m^{-2} in high yielding environments while under sub-humid temperate conditions of New Zealand, Ayaz et al. (2004b) proposed a doubling of optimum chickpea PPD from 50 to 100 plants m^{-2} in order to achieve maximum seed yield.

Twelve out of the total of 14 treatment responses resulted in 23% or higher seed yield advantage of maximum yield PPD (ranging from 53 to 65 plants m^{-2}) over the currently recommended

Table 3.11 Average chickpea maximum yield plant population density (Max. yield PPD), maximum yield, yield at recommended PPD (44 plants m⁻²) and percentage Max. yield PPD over recommended yield for Swift Current and Saskatoon.

	Swift Current				Saskatoon			
	Max. yield PPD (plants m ⁻²)	Maximum yield (g m ⁻²)	Yield at 44 plants m ⁻² (g m ⁻²)	% Max. yield PPD over 44 PPD	Max. yield PPD (plants m ⁻²)	Maximum Yield (g m ⁻²)	Yield at 44 plants m ⁻² (g m ⁻²)	% Max. yield PPD over 44 PPD
<u>Leaf type^z</u>								
Fern	56	261	207	26%	58	188	151	25%
Unifoliate	65	162	109	49%	60	112	87	29%
<u>Growth habit^y</u>								
Bushy	56	249	203	23%	49	195	194	0%
Erect	53	200	163	23%	58	147	120	23%
Spreading	55	244	194	26%	54	201	184	9%
<u>Seed class^z</u>								
Desi	61	271	201	35%	61	197	152	29%
Kabuli	56	202	159	27%	56	137	108	27%

^z Average from 2002 to 2005 for Swift Current and 2002 to 2004 for Saskatoon

^y Average from 2003 to 2005 for Swift Current and 2003 and 2004 for Saskatoon

optimum PPD (Table 3.11). Therefore, considering all location-years, the overall seed yield advantage of a higher optimum PPD over the currently recommended PPD cannot be over-emphasized. The results of this research therefore suggests that taking advantage of a higher seed yield average over the long term as compared to periodic low seed yield episodes will be more profitable to producers. This supports the high-yield-system-in-place (HYSIP) concept proposed for soybean production systems in Ohio, United States, where over a period of 10 years, the average seed yield of a solid-seeded-semidwarf narrow-row system was found to be 23 to 24% higher than a wide-row-indeterminate system although no seed yield advantage (i.e., seed yield neutral) was noted in a total of four location-years (Cooper, 1989).

In addition to an increased seed yield potential, a higher optimum PPD could also lead to a competitive advantage of the chickpea crop over weeds (Anderson 2005) and therefore a reduction in the cost of controlling weeds and thus result in an overall higher profit margin for producers. Another advantage of a higher optimum PPD is early maturity. Gan et al. (2003a) reported a 2.1 to 3.0 day reduction in maturity with PPD increase on the Canadian Prairies.

For treatment responses averaged over three and four years, i.e., from 2002 to 2004 for Saskatoon and 2002 to 2005 for Swift Current, respectively, percentage yield increase of maximum yield PPD over recommended PPD was at least 25%. However, where treatment responses were averaged over two years, i.e., 2003 and 2004, seed yield advantages of 0 and 9% of maximum yield PPD over recommended PPD were noted for the bushy and spreading growth habits, respectively, in Saskatoon. Otherwise, treatment responses ranged from 23 to 26% (Table 3.11) in Saskatoon. The challenging seasonal conditions in 2004 comprising of relatively late seeding, excessive moisture, early frost, snow and a late harvest may have contributed to the neutral (0%) and low (9%) yield advantages for the maximum yield PPD over the recommended PPD observed. Although Swift Current also received excessive moisture in 2004, i.e., a total of 299 mm in Swift Current vs. 296 mm in Saskatoon, seeding and harvesting were 11 and 27 days earlier, respectively, in Swift Current. Overall seed yield in Swift Current was about double that of Saskatoon (Fig. 3.2) and seed yield advantage of maximum yield PPD over recommended PPD was at least 23% for all treatments in Swift Current (Table 3.11).

Regarding the effect of canopy architecture on maximum yield PPD, cultivars with unifoliate leaves generally required a higher PPD to produce maximum yield than cultivars with fern leaves. Maximum yield PPD was higher for unifoliate cultivars by 8%, 16%, 30% and 33% in four location-years, slightly lower by 8% and 6% in two location-years and the same as the fern cultivars in one location-year. A higher maximum yield PPD for unifoliate cultivars than fern cultivars may be due to the fact that unifoliate leaves have a smaller surface area than fern leaves (Bueckert and Hovland, University of Saskatchewan, Canada, unpublished data; Bonfil, Goren, Mufradi, Lichtenzweig and Abbo, Agricultural Research Organization, Gilat Research Center, Israel, unpublished data in Bonfil et al., 2007) and therefore at a given PPD, the unifoliate canopy may be more open than the fern canopy. In this research, cultivars with fern leaves showed a more closed canopy than the unifoliate cultivars by having a significantly higher percentage maximum light interception in all location-years (Chapter 4: Table 4.2). A higher optimum PPD may therefore be required for unifoliate cultivars to achieve adequate canopy closure in order to intercept sufficient light for maximum biomass accumulation and seed yield.

No consistent pattern was observed in the relationship of optimum PPD with growth habit. Nienhuis and Singh (1985) found that bushy dry bean (*Phaseolus vulgaris* L.) required higher PPD to maximize yield than semi-viney and viney dry bean genotypes and attributed this response to low phenotypic plasticity of the more determinate bushy habit. Although all chickpea cultivars in Saskatchewan are indeterminate, the degree of indeterminacy varied both within and amongst growth habits in this research, with CDC Cabri, a bushy cultivar, being highly indeterminate. Assessing growth habits with similar degrees of indeterminacy may therefore be required to reveal differences in maximum yield PPD or optimum PPD of varying chickpea growth habits.

Desi chickpea cultivars had a higher maximum seed yield PPD than kabuli cultivars in all but one location-year which agrees with the higher optimum PPD (40 to 45 plants m⁻²) for desi chickpea and the lower optimum PPD (35 to 40 plants m⁻²) for kabuli chickpea suggested by Gan et al. (2003a) for the Brown Soil zone of the Canadian Prairies.

3.4.2 Actual Crop Stand

Percentage of actual relative to target stand counts decreased with increasing PPD in all location-years. This result supports other studies on the Canadian Prairies on chickpea by Miller et al. (2001), Gan et al. (2003a) and Li et al. (2006) and on lentil by Hanlan et al. (2006). Miller et al. (2001) reported a four-year mean emergence rate of 52% for chickpea and 47% for lentil in the Brown Soil zone when the crops were seeded at 75 plants m⁻². Jettner et al. (1999) also reported an overall 54% emergence rate for chickpea in Australia. Reasons attributed for low stand counts include mechanical damage to seed during transportation and seeding, poor seed bed and more competition at higher PPDs. Factors that may have contributed to low stand counts in this research were low total rainfall and low temperatures at seeding as well as possible mechanical damage to seeds during pre-seeding treatment which involved vigorous shaking of seeds and fungicidal mixture to ensure adequate coating of seeds.

However, Gan et al. (2003c) and Gan et al. (2003d) reported a seedling germination range of 96 to 98% and a minimum of 79% actual to target stand count in a study where chickpea was seeded at a range of 20 to 50 plants m⁻², which indicates that high emergence rates in chickpea could be achieved on the Canadian Prairies. High percentage chickpea crop establishment has also been reported elsewhere by Beech and Leach (1988) and Leach and Beech (1989). The causes of the low emergence rates in chickpea warrant urgent study if higher PPD is to be achieved to maximize seed yield.

3.4.3 Lowest Pod Height

In this research, lowest pod height was found to significantly increase with increasing PPD, similar to the finding of Jettner et al. (1999) and Gan et al. (2003a). This implies that increasing the optimum PPD of chickpea on the Canadian Prairies would lead to easier combine harvesting by allowing the combine header to be raised to avoid stones and rocks, which tend to cause equipment damage adding to the total cost of the farm operation.

3.4.4 Disease Severity

A major concern of a high PPD in crop production, in general, is the risk of higher disease incidence when individual plants are in closer proximity to each other, thus facilitating easy

transfer of pathogens within a crop stand. Denser canopies resulting from higher PPDs may also provide a more favorable environment for disease development due to changes in light penetration, air-flow and humidity (Burdon and Chilvers, 1982; Siddique and Bultynck, 2004). On the Canadian Prairies, however, Gan et al. (2003b) reported a decreasing trend in the response of ascochyta blight severity to increasing PPD (actual PPD of 26 to 76 plants m⁻²) while Gan et al. (2007) reported that under high ascochyta blight severity conditions (mean ascochyta blight severity of 35%), ascochyta blight severity increased as PPD (actual PPD of 21 to 70 plants m⁻²) increased in four cultivars but had no effect on two cultivars and even decreased in one cultivar.

No significant effect of increasing PPD on ascochyta blight severity was detected at five out of 8 growth stage-years but the remaining three growth stage-years, i.e., the late pod stages in 2003 and 2004 and the early flower stage in 2004, showed significant increases in ascochyta blight severity with increasing PPD (Table 3.9). The results of this research therefore indicate that increasing the recommended PPD would not lead to detrimental effects of ascochyta blight severity in chickpea on the Canadian Prairies, especially when combined with good agronomic practices. Such practices include use of cultivars with improved resistance to ascochyta blight, use of seeds with zero or close to 0% ascochyta blight levels, use of seed fungicidal dressings and seeding on land where chickpea has not been seeded in the previous four years (Saskatchewan Pulse Growers, 2000).

Cultivars with fern leaves exhibited significantly lower ascochyta blight severity than cultivars with unifoliolate leaves at all growth stage-years, supporting the results of other studies on the Canadian Prairies (Chongo et al. 2002; Gan et al., 2003b; Ahmed et al., 2006; Gan et al., 2007). Under Mediterranean conditions, Bonfil et al. (2007) also reported significantly better ascochyta resistance of F₄ and F₅ chickpea lines with fern leaves than lines with unifoliolate leaves at the pre-podding stage, although no significant differences in ascochyta resistance were noted at the pre-flowering stage.

Ascochyta blight severity differed significantly among growth habits with the spreading cultivar having the lowest ascochyta severity followed by the bushy cultivars and the erect cultivars

having the most ascochyta blight severity (Table 3.9). The bushy and spreading cultivars had denser canopies than the erect cultivars as evidenced by higher percentage maximum light interception relative to the erect cultivars (Chapter 4: Table 4.2). Although the erect cultivars formed a more open canopy and are therefore expected to create a microclimate less favorable for disease development, two of the four erect cultivars studied had unifoliolate leaves which exhibited high ascochyta severity and may therefore have contributed to the overall high ascochyta blight severity of the erect growth habit. Conversely, all bushy cultivars as well as the spreading cultivar had fern leaves which showed relatively lower ascochyta severity, hence the lower ascochyta severity observed in the bushy and spreading cultivars. Gan et al (2007) reported that cultivar type together with environmental conditions and PPD are the main factors influencing ascochyta severity in chickpea, therefore the inherent ascochyta resistance of the individual cultivars may have been a factor in the responses observed. Canopy architecture effects such as leaf type and growth habit, however, have a significant role to play in the overall integrated management of ascochyta in chickpea.

3.4.5 Individual Seed Weight

Within the range of PPDs studied, individual seed weight increased significantly in response to increasing PPD in three location-years but the reverse trend was observed in one location-year i.e. 2005, all in Swift Current in the Brown Soil zone (Table 3.10). The increasing individual seed weight in response to increasing PPD may be due to production of many small seeds per plant with low individual seed weight at low PPD. At high PPDs fewer but relatively larger seeds per plant and therefore higher individual seed weight may also be produced. For example, Liu et al. (2007) reported that as PPD increased, seed number per plant decreased while individual seed weight increased in soybean. Liu et al. (2003) reported a halving of the number of fertile pods per plant in chickpea as PPD increased from 20 to 50 plants m⁻² although PPD did not have any significant effect on individual seed weight. Various studies on chickpea have pointed to a stable individual seed weight with increasing PPD (Siddique et al. 1984; Gan et al. 2003a; Gan et al. 2003b, Gan et al. 2003d). Individual seed weight did not increase under wet conditions and decreased under dry conditions (Beech and Leach, 1989; Gan et al. 2003a) due to incomplete seed-filling in drought. High disease severity observed in 2005 may have contributed to the reduced seed weight at high PPD. Ascochyta blight severity ranging from 33 to 41% was

observed in 2005 and disease severity increased as PPD increased at the late podding stage, although not significantly. The results of this research suggest that increasing optimum PPD from the currently recommended PPD of 44 plants m^{-2} to 55 plants m^{-2} PPD would not negatively impact individual seed size.

3.4.6 Seed Yield

Overall, cultivars with fern leaves produced significantly higher seed yield than cultivars with unifoliolate leaves in both locations, as well as in both dry and wet years. Similarly, seed yield advantage of kabuli chickpea cultivars with fern leaves over cultivars with unifoliolate leaves has also been reported on the Canadian Prairies by Li et al. (2006) and in India by Srinivasan et al. (2006). Cultivars with bushy and spreading growth habits also yielded better than erect cultivars. Rubio et al. (2004) reported higher seed yield in chickpea lines with bushy growth habit than erect lines in all environments and ascribed the yield difference to a higher number of primary and secondary branches per plant and total reproductive nodes in the bushy lines. Knights (1984) also reported higher seed yield in semi-erect chickpea lines than erect lines due to higher primary branching in the semi-erect lines. In this research, number of nodes on the main-stem was significantly higher in the spreading cultivar but did not differ significantly between the erect and bushy cultivars which presupposes that the bushy habit is a result of more secondary and tertiary branching rather than primary branching.

The results of this research demonstrate that fern leaves together with bushy and spreading growth habits are traits that should be combined, and together with increasing the recommended optimum PPD, would maximize chickpea seed yield in the short-season and moisture limited crop production systems of the Canadian Prairies.

4.0 Canopy Architecture and Plant Density Effect on Light Interception and Utilization, Biomass and Harvest Index in Short-Season Chickpea (*Cicer arietinum* L.)

4.1 INTRODUCTION

Over 90 % of Canadian chickpea (*Cicer arietinum* L.) production is within the Brown Soil and drier regions of the Dark Brown Soil zones of the Prairies (Gan and Noble, 2000). Crop production is challenged by a short growing season (May to August), limited heat units as well as low and variable moisture. Suitable agronomic practices and chickpea cultivars with canopy architecture traits which best utilize the limited resources could be exploited to maximize and stabilize seed yield in adapting chickpea to this environment.

Crop yield is a function of the biomass produced during the growing season and the partitioning of the biomass to seed yield (Sinclair, 1993). Agronomically, conversion of biomass to seed yield is expressed as harvest index (HI) where seed yield equals the product of HI and biomass (Donald, 1962). Accumulation of biomass through photosynthetic conversion of CO₂ depends on the seasonal or cumulative intercepted radiation (RI) by the canopy in the absence of stress, such as moisture, nutrients and pests. Radiation use efficiency (RUE) is the efficiency of conversion of the intercepted radiation to biomass (Monteith, 1977). Gallagher and Biscoe (1978) defined yield as the product of RUE, RI and HI, a relationship that removes confounding factors such as time, vagaries of weather and varying agronomic practices from the analysis and allows comparison to be made easily across production systems. Radiation use efficiency is about 1.4 g MJ⁻¹ on a total solar radiation basis, i.e. 2.8 g MJ⁻¹ photosynthetically active radiation (PAR), for many temperate crops (Monteith, 1977). A RUE review by Sinclair and Muchow (1999) reported values of 1.53 and 0.67 g MJ⁻¹ for chickpea on a total solar radiation basis, i.e., 3.06 and 1.34 g MJ⁻¹ PAR.

Studies in environments other than the Canadian Prairies have compared grain legumes, including chickpea (Thomson and Siddique, 1997; Ayaz et al., 2004a), as well as evaluated chickpea responses to radiation interception and utilization in the adaptation of chickpea to new environments (Hughes et al., 1987; Beech and Leach 1988; Leach and Beech, 1988; Mwanamwenge et al., 1997). Hughes et al. (1987) indicated that both growth habit and plant population density (PPD) had minimal effects on biomass production, but while high PPD was advantageous over lower PPD with respect to intercepted radiation, no significant differences were noted between prostrate and erect growth habits. Radiation use efficiency was greater for the erect growth habit and the lower PPD, however, growth habit and PPD were highly confounded. Leach and Beech (1988) revealed the importance of maximizing RI through narrow row-spacing. Mwanamwenge et al. (1997) found percentage PAR absorption to be related to the rate of canopy development in a short-season Mediterranean-type environment. Ayaz et al. (2004a) reported a significant increase in green area index, RI and RUE with increasing PPD while biomass, yield and HI strongly correlated with RI under sub-humid temperate conditions.

In short-season environments, a combination of canopy traits and high PPD, which lead to rapid radiation capture through early canopy closure, may be required to improve yield in chickpea. Chickpea cultivars available in Saskatchewan have two leaf types, fern and unifoliate, and three growth habits, bushy, erect and spreading. Leaf type and growth habit are each under the control of single Mendelian genes (Muehlbauer and Singh, 1987). The currently recommended PPD for chickpea production in Saskatchewan is 44 plants m^{-2} (Saskatchewan Pulse Growers – Pulse Production Manual, 2000). A tentative optimum PPD of 40 to 45 plants m^{-2} for desi chickpeas and 35 to 40 plants m^{-2} for kabuli chickpea based on a study of four cultivars and a limited range of PPDs of 20 to 50 plants m^{-2} was also set for the Brown Soil zone by Gan et al. (2003a). Information is lacking on the effect of leaf type, growth habit and PPD on growth and yield parameters in both desi and kabuli chickpea in the chickpea producing regions of North America, especially under the high-latitude temperate short-season conditions of the Canadian Prairies.

The objectives of this current experiment were to (i) assess LI, RI, biomass, RUE and HI of chickpea cultivars varying in leaf type and growth habit at a range of PPDs and (ii) explore associations between seed yield and growth parameters. The ultimate goal was to identify

parental traits which best utilize the available radiation in the short-season Prairie environment for use in chickpea breeding programs.

4.2 MATERIALS AND METHODS

4.2.1 Experimental Design

The experimental design was as described in Chapter 3 (Section 3.2.1). Briefly, experiments were conducted over eight location-years i.e. Swift Current from 2002 to 2005, Saskatoon from 2002 to 2004. One location-year (Elrose, 2002) was excluded from the analysis because of severe drought and grasshopper infestation (Table 3.1). Seeding and harvest dates, plot size and number of rows are also presented in Table 3.1. Eight cultivars, namely CDC Anna, CDC Cabri, CDC ChiChi, CDC Ebony, CDC Xena, Evans, Myles and Amit, with a range of leaf types and growth habits were seeded as described in Table 3.2. For each location-year, the experimental design was a randomized complete block design with a factorial combination of cultivar and PPD and treatment combinations were replicated four times.

4.2.2 Data Collection and Calculations

Stand counts were determined at about the 4-node stage from two or three randomly selected 1-m sections of three different rows per plot. From the 6-node stage until physiological maturity, biomass was cut at ground level from a bordered area of 0.31m^2 (0.25 m across four rows) per plot at approximately 7 to 14-day intervals, depending on weather conditions. Senesced leaves were not removed from the plants.

On or about the same day as biomass was sampled, when skies were cloudless between 11:00 am and 2:00 pm, and incident irradiance was over $1500\ \mu\text{mol s}^{-1}\ \text{m}^{-2}$, spot PAR measurements of light interception (LI) were determined by taking one above canopy and three below canopy measurements of PAR for each plot using a hand-held 1-m line quantum sensor (Li-Cor LI-191SA, Lincoln, NE). Above- and below-canopy radiation measurements were also logged continuously using tube solarimeters (Delta-T DL2e, Cambridge, UK) for a subset of cultivar-target PPD combinations i.e. CDC Cabri, CDC ChiChi, CDC Ebony and CDC Xena at 30, 60 and 85 plants m^{-2} , over 3 replications in 2004 and 2005 in Saskatoon (Dark Brown Soil zone) and Swift Current (Brown Soil), respectively. In both cases, the light-measuring instruments were placed perpendicular to four rows within the plot. All plots at Swift Current had six rows

while plots at Elrose and Saskatoon in 2002 had four rows, plots at Saskatoon in 2003 had 8 rows and plots at Saskatoon in 2004 had 16-rows (Table 3.1). Percentage LI was calculated as:

$$LI (\%) = 1 - (\text{average PAR below canopy} / \text{PAR above canopy}) \times 100 \quad [4.1]$$

Best fitting linear, quadratic or cubic models were used to describe the daily response of fractional LI per plot based on the highest adjusted R^2 values of the model and inspection of the predicted curves and actual data. Cumulative intercepted radiation of a given plot was obtained by integrating the product of percentage LI and total daily radiation (converted to PAR by a factor of 0.5, Monteith, 1972) from emergence to physiological maturity. RUE was calculated as the slope of the biomass by RI regression line over the period of linear canopy growth. In addition to mean air temperature and rainfall (Table 3.3), solar irradiance was also logged daily using automated weather stations at both Swift Current and Saskatoon, except for Saskatoon in 2002 where environmental data was obtained from the University of Saskatchewan Weather Station at the Kernen Crop Research Farm (Table 4.1).

At harvest maturity, six plants were harvested, dried at 40 °C for about a week and weighed, after which the plants were threshed and the seeds weighed. Harvest index was calculated as the quotient of the seed and total plant weights. Plots were combined at harvest maturity and seeds dried at 40 °C for about a week and then weighed to obtain seed yield.

4.2.3 Statistical Analysis

All statistical analyses were performed using SAS version 9.0 (SAS Institute, 1999 Cary, NC, USA). Data were analyzed separately for each location-year because actual PPD attained varied over location-years and treatment effects were significantly different across years for each location (soil zone). Not all combinations of canopy traits (leaf type x growth habit) were available, so contrast statements were used to separate means for leaf types and growth habits to better understand cultivar and canopy architecture effects.

Table 4.1 Monthly solar radiation (MJ m^{-2}) in Swift Current (SC) in the Brown Soil zone (2002 to 2005) and Saskatoon (STN) in the Dark Brown Soil zone (2002 to 2004).

	Swift Current (Brown Soil zone)				Saskatoon (Dark Brown Soil zone)		
	2002	2003	2004	2005	2002 ^z	2003	2004
	<u>Solar radiation (MJ m^{-2})</u>						
May	339	303	280	305	393	372	330
June	294	314	325	284	347	352	332
July	354	379	333	376	385	381	330
Aug	243	275	261	272	307	320	288
Sept	198	180	213	211	235	- ^y	221
Total	1427	1450	1411	1448	1668	-	1501

^z University of Saskatchewan Weather Station at the Kernen Crop Research Farm

^y Missing data

For all variables, outliers were removed based on cultivar-target combinations using Student's Residual regressions and values greater than 2.0 or less than -2.0 were removed from the analyses (Appendix 2). Analysis of variance (ANOVA) of maximum LI, maximum biomass, RI, RUE, and HI were performed using the PROC MIXED procedure with replicate as random effect and cultivar and PPD as fixed effects. The default modified Tukey's statistic of the PROC MIXED procedure was used for mean separation at $P < 0.05$. Mean separation output were converted to letter groupings (Saxton, 1998). Actual PPD was also used to test for a linear and quadratic response of variables.

4.3 RESULTS

4.3.1 Weather Effects

The weather effects were as described in the Chapter 3 (Section 3.3.1). Briefly, the pattern of variation in the weather was similar in both locations (Table 3.3) and reflected the year-to-year variability of the weather on the Canadian Prairies. Rainfall in 2002, 2004 and 2005 was higher than the long-term average but 2003 had lower than average rainfall. Seasonal mean monthly temperatures were slightly below the long-term average in 2002 and 2005, but much cooler in 2004. In 2003, however, the mean seasonal temperature was above the long-term average.

Total seasonal cumulative radiation was also recorded for Swift Current in the Brown Soil zone and Saskatoon in the Dark Brown Soil zone as presented in Table 4.1. The total seasonal cumulative radiation was generally lower in Swift Current than in Saskatoon.

4.3.2 Light Interception

For each year, treatment responses were quite similar at the two locations. Graphs of LI (%) by days after seeding (DAS) for all treatments, i.e., leaf type, growth habit and PPD (Figs 4.1, 4.2 and 4.3) showed a general linear increase of LI up to a maximum LI (ranging from 62 to 91%) after which LI either remained fairly constant (Swift Current in 2002 and Saskatoon in 2004) or dropped slightly to about 60% (Swift Current in 2004 and 2005 and Saskatoon 2002). The slight decrease in LI was a result of available moisture during the later part of the growing season in the relatively wet years of 2002, 2004 and 2005. In the dry year of 2003, LI fell sharply following a quadratic pattern to about 20% from a peak of about 70% in Swift Current and about 62% in Saskatoon due to terminal drought, resulting in the earliest harvesting dates of 94 and 110 DAS in Swift Current and Saskatoon, respectively. The decrease in LI after reaching maximum LI was a function of leaf senescence and subsequent abscission.

With the exception of 2003, where maximum LI was attained around 60 DAS, maximum LI was reached much later at about 80 to 100 DAS in 2002 and 2004, respectively.

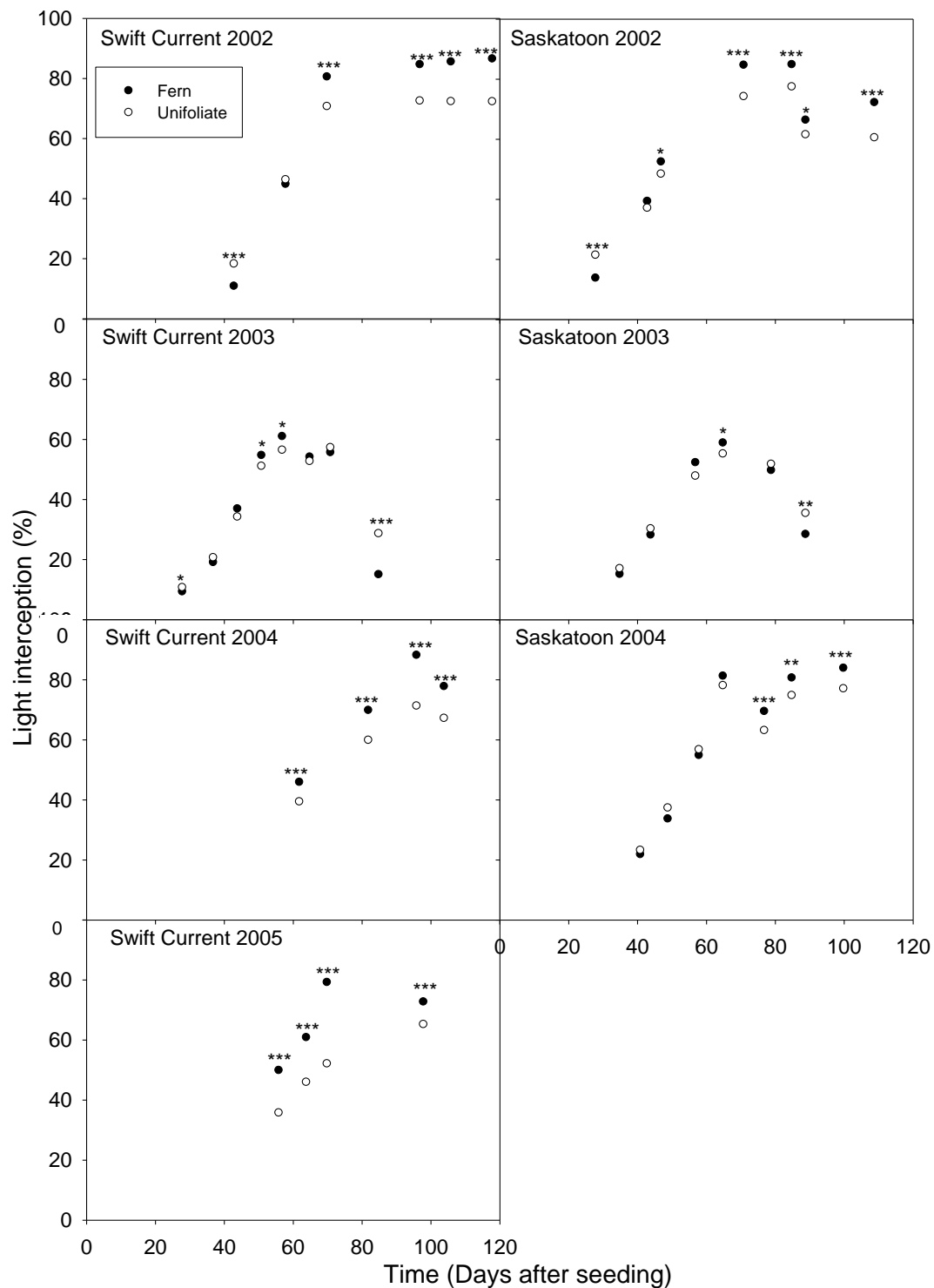


Fig. 4.1. Light interception of fern and unifoliolate leaf types in chickpea over the growing season in Swift Current the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001 , respectively.

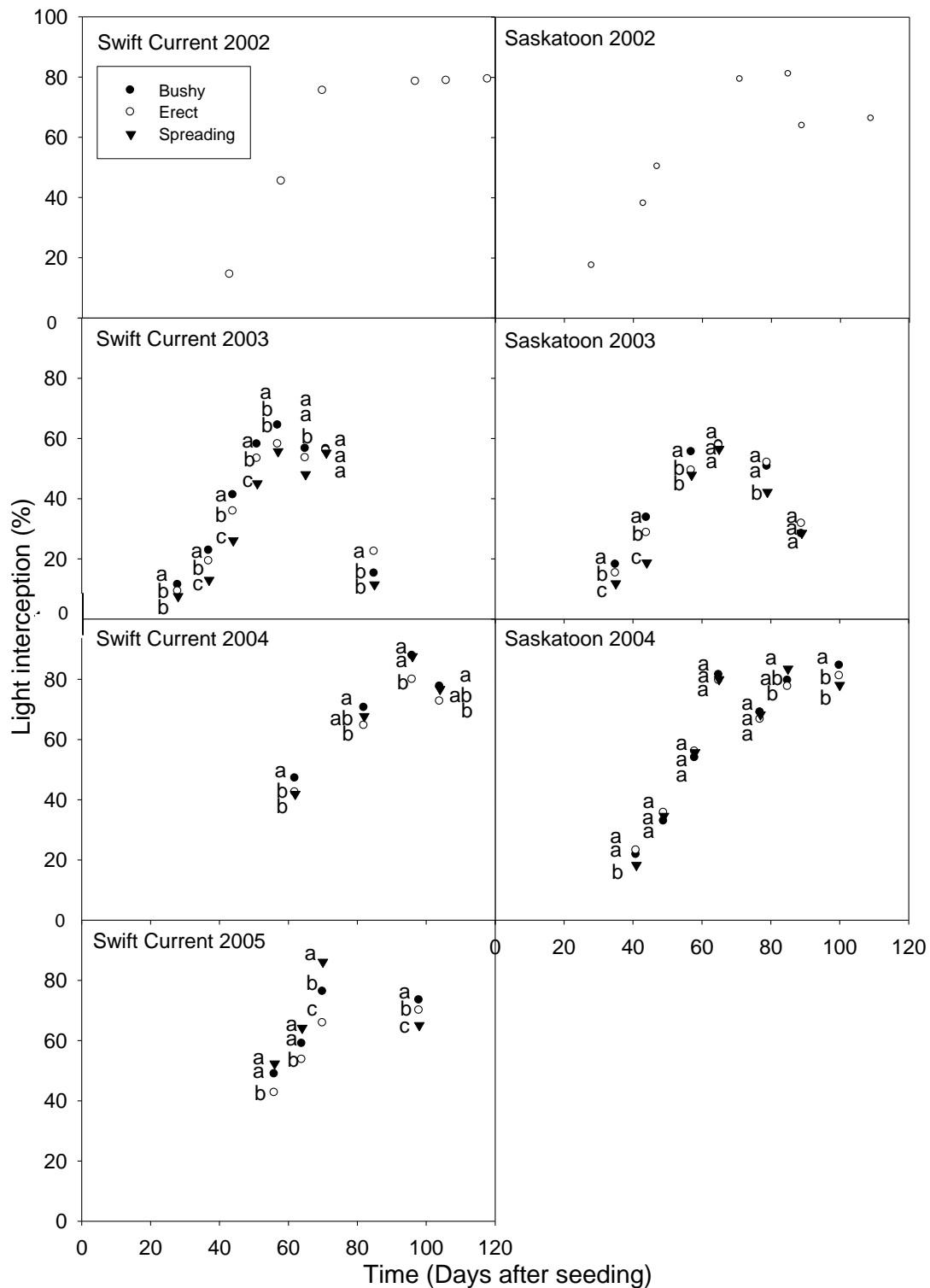


Fig. 4.2 Light interception of bushy, erect and spreading growth habits in chickpea over the growing season in Swift Current the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone in 2002 and 2004. Data points represent treatment means of four replications. Means with same letter are not significantly different at $P < 0.05$.

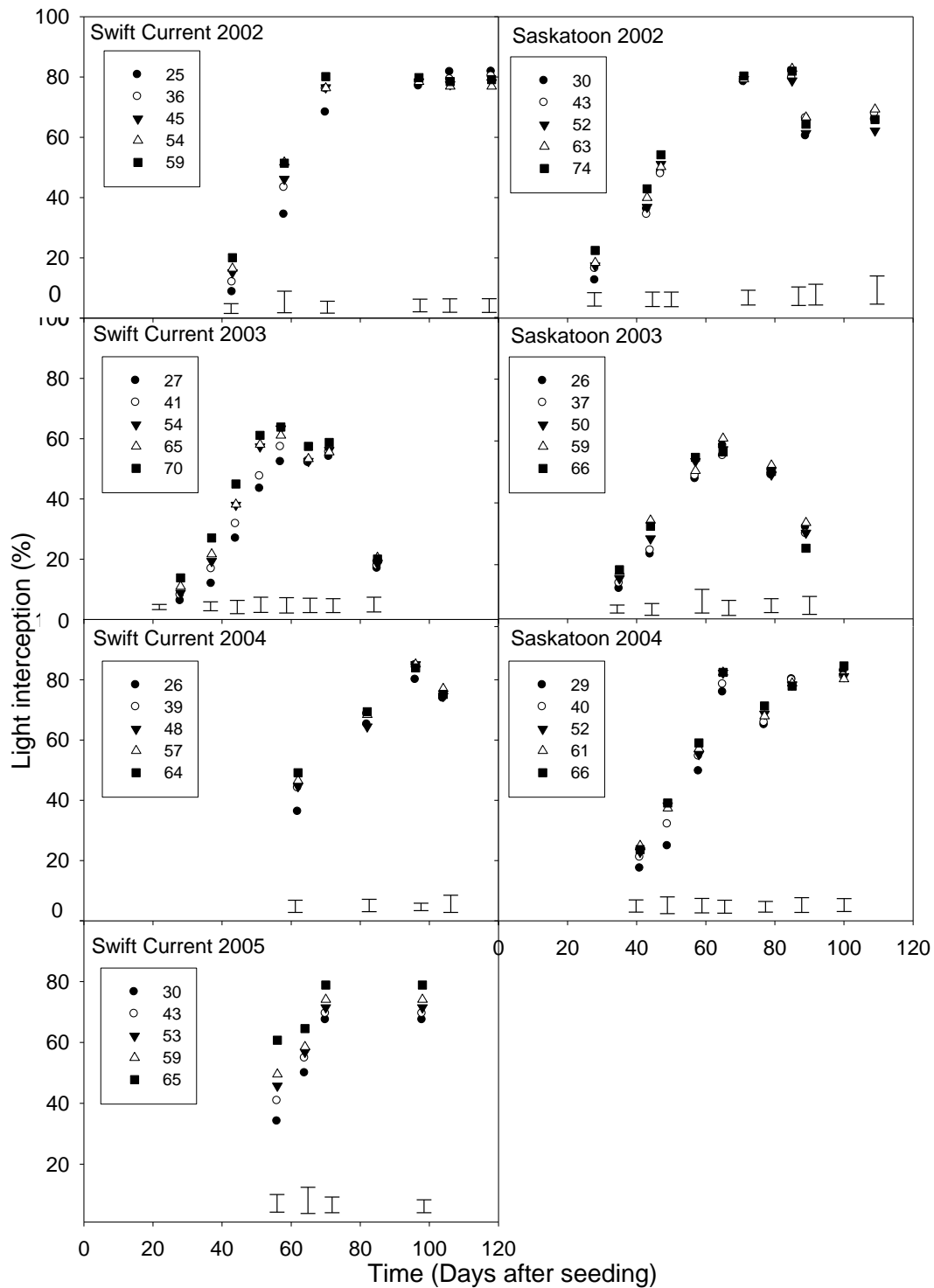


Fig 4.3 Light interception at five chickpea actual plant population densities over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. Error bars indicate LSD for a sampling day.

Although no measurement was recorded between 70 and 98 DAS in 2005, a fitted curve could place the maximum LI within the range of 80 to 100 DAS. This early attainment of maximum LI in 2003 could be due to the higher than normal temperatures that crop year which hastened crop development, implying the crop utilized light for biomass production for a relatively short period (Saxena, 1984). Coupled with the drought conditions that limited crop growth, seed yield averaged over all treatments in 2003 (126 g m^{-2}) was lower as compared to the other years, i.e., 178 g m^{-2} in 2002, 214 g m^{-2} in 2004 and 165 g m^{-2} in 2005.

4.3.2.1 Leaf Type Effects on Light Interception

Cultivars with unifoliolate leaves had significantly or non-significantly higher LI than those with fern leaves from emergence up to 30 to about 45 DAS, after which the fern-leaved cultivars either caught up with or overtook the unifoliolate types until the end of the season (Fig. 4.1). Lack of data points before 40 DAS in Swift Current in 2004 and before 55 DAS in 2005 may have failed to capture the early advantage of unifoliolate cultivars with respect to LI. This early LI advantage of the unifoliolate cultivars could be due to bigger seed size leading to early stand establishment and associated early vigor.

However, the fern-leaved cultivars had significantly higher maximum LI than the unifoliolate types in all location-years, except in Saskatoon in 2003, where cultivars with fern leaves still had a 5% higher maximum LI over the unifoliolate types (Table 4.2). Least maximum LI for both leaf types was observed in Saskatoon in 2003, i.e., 62 and 59% for the fern and unifoliolate leaf types, respectively. The highest maximum LI values recorded for fern and unifoliolate cultivars were 91 and 85%, respectively, in Saskatoon in 2004, which is an indication of insufficient canopy closure, i.e., at least 9 to 15% of incident solar radiation reached the soil surface and would have contributed to evaporative water loss and weed growth. The inability of the canopy to close was due to the 0.31 m row spacing, which is likely too wide, and the length of the growing season which is not long enough to permit plants to complete canopy closure.

Table 4.2 Effect of leaf type, growth habit and plant population density of chickpea on maximum light interception (%) over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in Dark Brown Soil zone from 2002 to 2004.

	Maximum light interception (%)						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
<u>Leaf type</u>							
Fern	90a ^z	90a	65a	62a	89a	91a	81a
Unifoliolate	77b	81b	62b	59a	75b	85b	66b
<u>Growth habit</u>							
Bushy			68a	62a	89a	90a	79b
Erect	83	85	63b	61a	83b	88a	74c
Spreading			63b	59a	88a	91a	86a
<u>Target (plants m⁻²)</u>							
30	85	84	59†	61	82†‡	89	72†
45	83	86	63	59	87	89	79
60	82	83	65	62	86	89	77
75	84	87	65	64	87	90	79
85	83	86	70	59	86	90	80

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

4.3.2.2 Growth Habit Effects on Light Interception

All cultivars seeded in 2002 had the erect growth habit as presented in Figs. 4.2, 4.5 and 4.8. From early in the season until maximum LI, the bushy cultivars showed superior LI than either the erect or spreading cultivars in three out of five location-years (Swift Current and Saskatoon in 2003 and Swift Current in 2004). Limited differences were observed among growth habits in Saskatoon in 2004 while in Swift Current in 2005 the spreading and bushy cultivars showed significantly higher LI than the erect cultivar up to the peak LI. After reaching peak LI, the bushy cultivars tended to have higher LI than the erect cultivars in three location-years (Swift Current in 2004 and 2005 and Saskatoon in 2004) but LI tended to be similar at both locations in 2003 while the spreading cultivar generally had a lower LI.

Regarding growth habit effect on maximum LI attained over the growing season, the erect cultivars tended to have the lowest maximum LI across location-years (Table 4.2). The bushy cultivars had significantly higher maximum LI in Swift Current in 2003 and together with the spreading cultivar in Swift Current in 2004. No significant differences were noted in Saskatoon in either 2003 or 2004 although the bushy habit had highest maximum LI in 2003 and the second highest in 2004. In Swift Current in 2005, all three growth habits were significantly different from each other with the spreading and erect growth habits having the highest and lowest maximum LIs, respectively. Interestingly, the highest maximum LI (91%) was observed for the spreading habit in Saskatoon in 2004 and the lowest maximum LI (59%) was noted for the same growth habit in the same location in 2003. Although these values were not significantly different from the other growth habits in the respective years, it suggests that the spreading habit is more responsive to moisture and light attenuation than the bushy and erect cultivars. In the relatively wet years of 2004 and 2005, the spreading cultivar once again had the highest maximum LI of 88 and 86%, respectively, in Swift Current.

4.3.2.3 Plant Population Density Effects on Light Interception

Generally, LI increased over the season, with the highest PPD having higher LI values on any given sampling date and the highest and smallest PPDs having significantly higher

and lower LI, respectively (Fig 4.3). The highest PPD (usually about 65 plants m⁻²) generally had higher LI throughout the growing season across all location-years. Differences between PPD treatments were generally larger at the beginning of the season but tended to become smaller as the season progressed, resulting in non-significant differences by the end of the season.

The PPD effect on maximum LI was minimal (Table 4.2). The difference between the highest and lowest maximum LI in a given location-year was not more than 10%, except Swift Current in 2003 where the difference was 19%. This suggests a high level of growth compensation in chickpea, in that individual plants at low PPD maximize growth at the expense of the more available resources such as moisture and light, whereas individual plant growth is limited at high PPD due to inter-plant competition. There was no consistent effect of PPD on maximum LI attained over the growing season across all location-years. Significant differences were observed in three out of the seven location-years but no differences were detected in the remaining location-years. However, where significant differences were observed, there was an increasing trend in maximum LI with increasing PPD. Highest maximum LI (90%) was noted for the two highest PPDs in Saskatoon in 2004 while the lowest LI (59%) was noted for the 30 plants m⁻² target PPD in Swift Current in 2003 and the 45 plants m⁻² target PPD in Saskatoon of the same year.

Response of maximum LI to PPD was different between locations. In Swift Current, three out of the four locations-years showed significant differences with respect to effect of PPD on maximum LI while no significant differences were observed in Saskatoon. The lack of differences in Saskatoon in the Dark Brown Soil zone which is generally a moister environment than Swift Current in the drier Brown Soil zone could be due to available moisture which may be contributing to indeterminate growth thus masking any apparent differences in crop growth and hence maximum LI. In addition, the cultivars are generally adapted to the Brown Soil zone.

4.3.3 Cumulative Intercepted Radiation

With respect to leaf type, growth habit and PPD, the amount of intercepted light accumulated over the growing season, i.e., RI, increased linearly with DAS in all location-years (Figs 4.4, 4.5 and 4.6).

4.3.3.1 Leaf Type Effects on Cumulative Intercepted Radiation

Generally, from early to mid-season, the unifoliolate-leafed cultivars had greater cumulative intercepted (RI) than the fern-leafed cultivars, either significantly in both locations in 2002 and in Saskatoon in 2003 or non-significantly in Swift Current in 2003 and Saskatoon in 2004 (Fig 4.4). From mid-season onwards, the fern-leafed cultivars attained either similar RI (both locations in 2003; Saskatoon in 2004) or higher RI than the unifoliolate cultivars, becoming significant by the end of the season (both locations in 2002; Swift Current in 2004 and 2005). No significant differences were observed in Swift Current in 2003 and Saskatoon in 2004, although in both locations, a similar pattern of higher RI for the unifoliolate cultivars early in the season and higher RI for fern cultivars later in the season was still evident.

Fern cultivars attained significantly higher maximum RI by the end of the season than the unifoliolate cultivars in all but the two locations in 2003 (Table 4.3). The highest maximum RI attained was 419 and 399 MJ m⁻² for the fern and unifoliolate cultivars, respectively, in Swift Current in 2002. The lowest maximum RI was 221 MJ m⁻² for the fern leaf type and 215 MJ m⁻² for the unifoliolate leaf type in Swift Current and Saskatoon, respectively, in 2003, the driest experiment year.

4.3.3.2 Growth Habit Effects on Cumulative Intercepted Radiation

Cultivars with the bushy growth habit generally had a greater RI over the growing season than either the erect or spreading cultivars, except in the Saskatoon in 2004 where no differences were noted amongst growth habits. The RI of the erect and spreading growth habits was generally

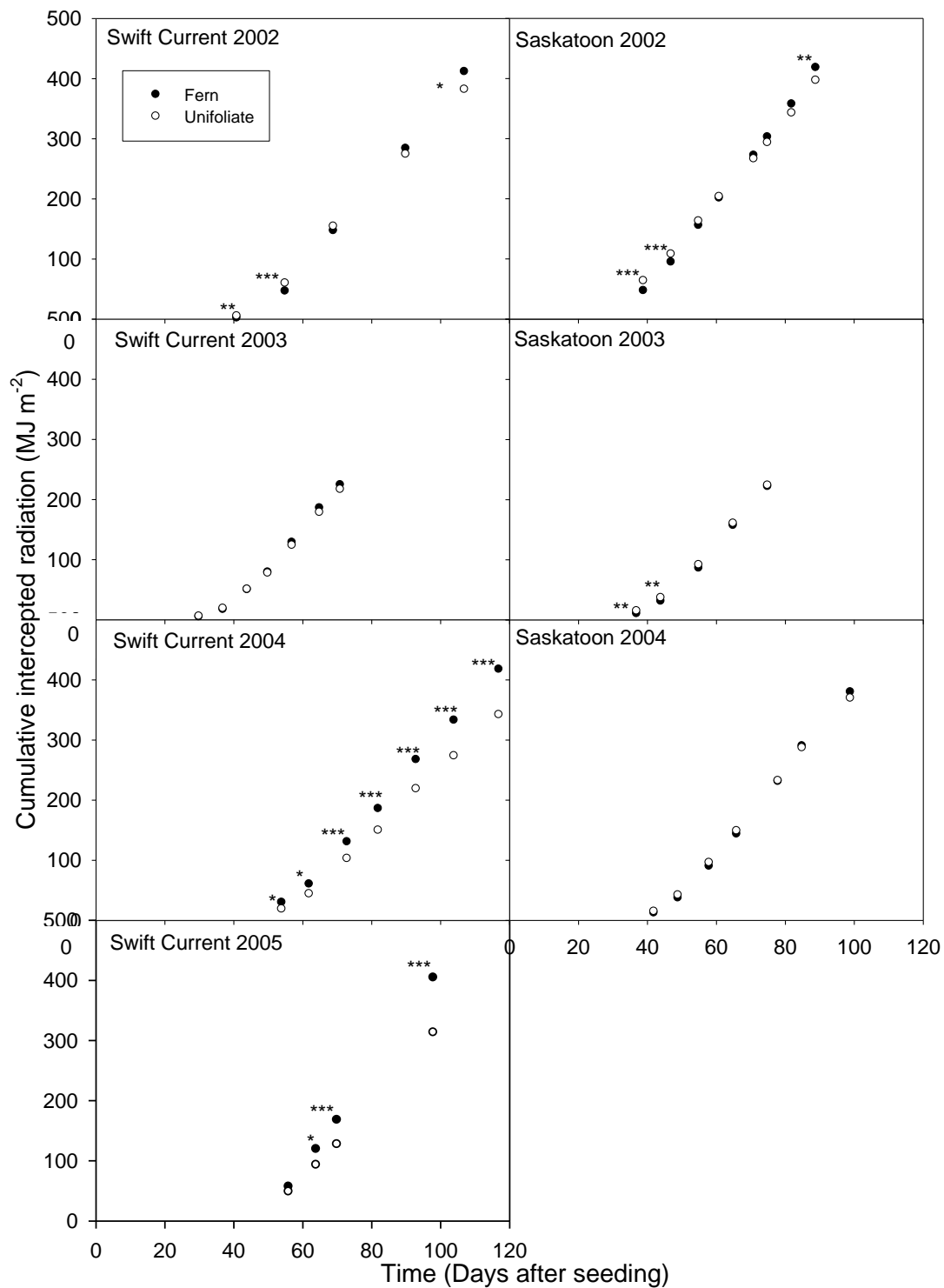


Fig. 4.4 Cumulative intercepted radiation of fern and unifoliate leaf types in chickpea over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001, respectively.

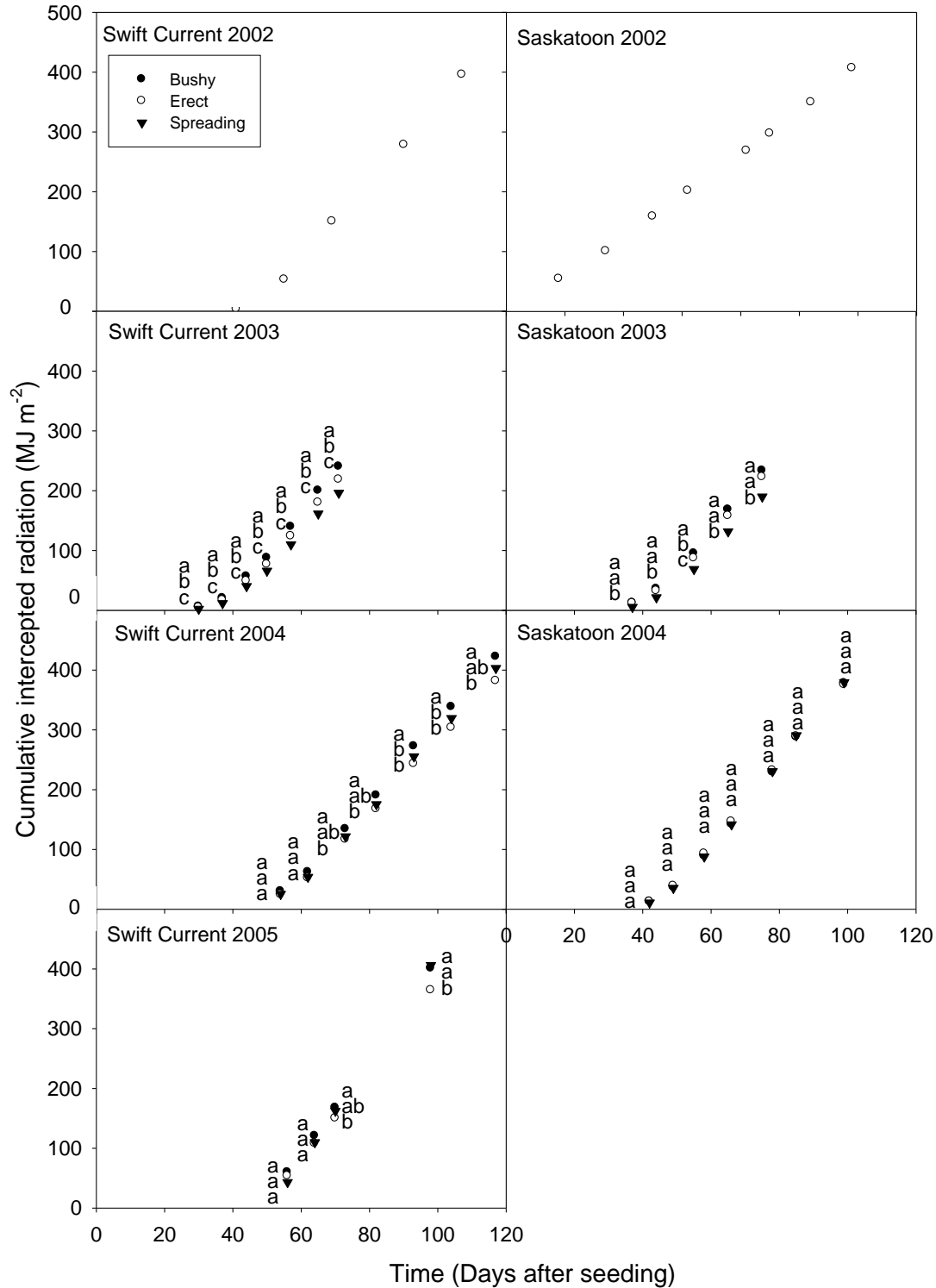


Fig. 4.5 Cumulative intercepted radiation of bushy, erect and spreading growth habits in chickpea over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone in 2002 and 2004. Data points represent treatment means of four replications. Means with same letter are not significantly different at $P < 0.05$.

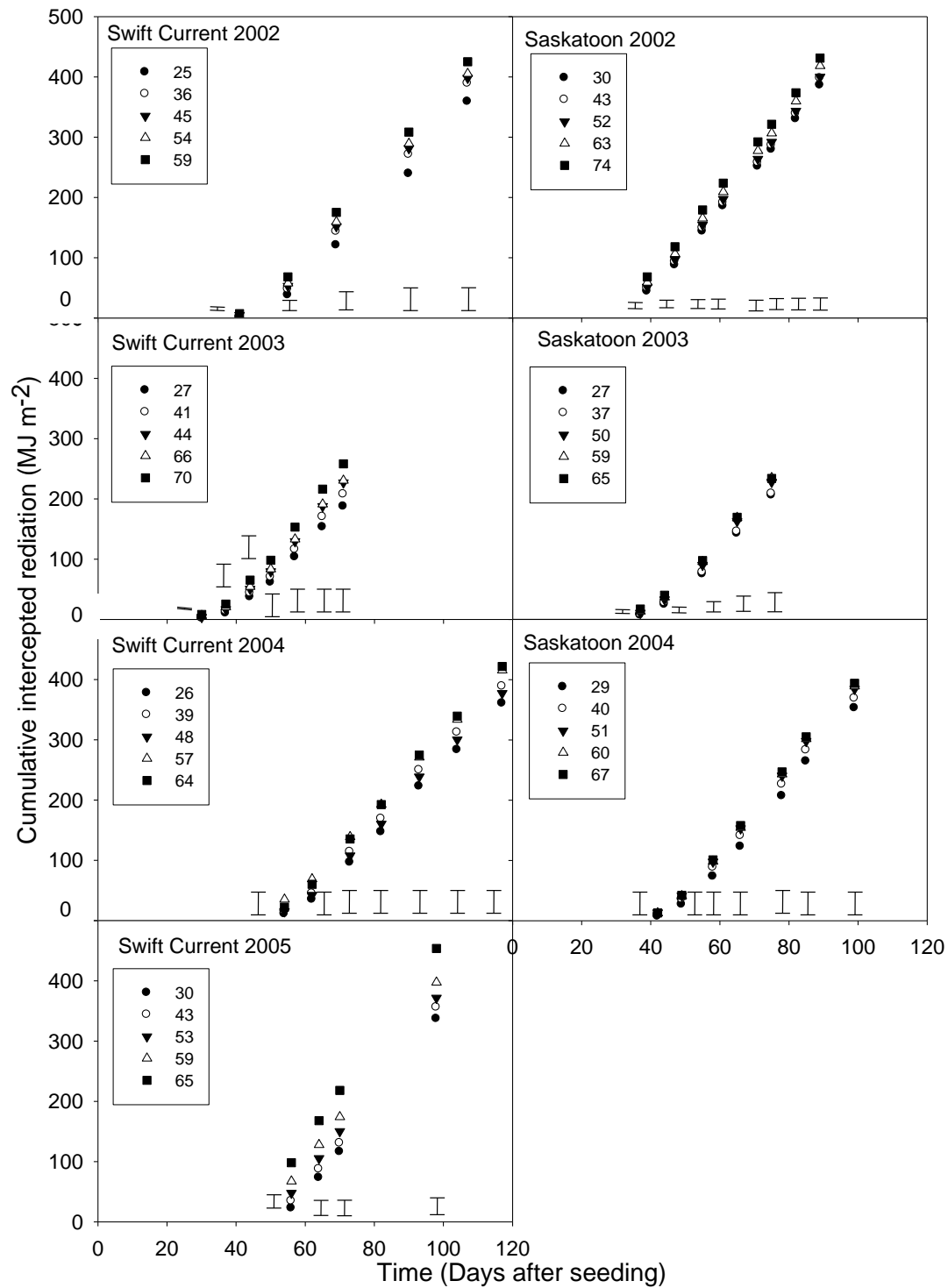


Fig. 4.6 Cumulative intercepted radiation at five chickpea actual plant population densities over the growing season in Swift current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. Error bars indicate LSD for a sampling day.

Table 4.3 Effect of leaf type, growth habit and plant population density of chickpea cultivars on cumulative intercepted radiation (MJ m^{-2}) over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

	Cumulative intercepted radiation (MJ m^{-2})						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
<u>Leaf type</u>							
Fern	411a ^z	419a	223a	221a	410a	377a	362a
Unifoliolate	386b	399b	215a	226a	345b	367b	266b
<u>Growth habit</u>							
Bushy			239a	233a	421a	374a	359a
Erect	398	410	219b	224a	374b	375a	316b
Spreading			196c	192b	390b	373a	366a
<u>Target (plants m^{-2})</u>							
30	361†‡	392†	188†	205†	366†‡	351†	282
45	389	389	206	208	390b	367	318
60	407	402	226	233	396ab	377	331
75	409	419	229	234	407ab	388	356
85	423	435	257	229	418a	392	410

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

similar (Fig 4.5). The effect of growth habit on RI was similar in both locations in 2003 where the bushy cultivars had the highest RI followed by the erect cultivars and the spreading cultivars having significantly lower RI on most sampling dates. In 2004, the response in Swift Current was similar to that of 2003, except that the erect and spreading cultivars were not significantly different from each other but both were significantly lower than the bushy types. In Saskatoon in 2004, however, no significant differences were noted, although the spreading cultivar still tended to have the lowest RI. In Swift Current in 2005, no significant differences were observed early in the season but the bushy and spreading cultivars (401 MJ m^{-2} and 406 MJ m^{-2} , respectively) showed an advantage over the erect cultivars (364 MJ m^{-2}) by the end of the season (Fig. 4.5).

In the five location-years where all three growth habits were studied, the bushy cultivars either had significantly higher maximum RI (Swift Current in 2003 and 2004) or similar maximum RI with each of the erect (Saskatoon 2003) and spreading growth habits (Swift Current 2005) as shown in Table 4.3. Maximum RI of the spreading cultivar was significantly lower than the erect cultivars only in 2003 in both locations which may be an indication that the spreading cultivar performs poorly under drought conditions. The bushy cultivars attained the highest RI (421 MJ m^{-2}) in Swift Current in 2004 while the lowest maximum RI (192 MJ m^{-2}) was attained by the spreading cultivar in Saskatoon in 2003.

4.3.3.3 Plant Population Density Effects on Cumulative Intercepted Radiation

For PPD, the response of RI to DAS was similar across location-years (Fig 4.6). On a given DAS, RI generally increased in the order of increasing PPD with the two highest PPDs having the highest RIs. Differences amongst PPDs increased as the season progressed. The relatively short growing season of 2003 limited RI as the highest PPD accumulated was less than 300 MJ m^{-2} in both locations, whereas in the wet years (2002, 2004 and 2005) the highest PPD accumulated at least 400 MJ m^{-2} .

Maximum RI increased with increasing PPD in all location-years with the exception of Swift Current in 2005 (Table 4.3). The highest RI (435 MJ m^{-2}) was obtained at the highest PPD (85 plants m^{-2} target) in Saskatoon in 2002 while the lowest maximum RI (188 MJ m^{-2}) was achieved at the lowest PPD (30 plants m^{-2} target) in Swift Current in 2003, the driest year.

4.3.4 Biomass Accumulation

Time-course graphs (Figs. 4.7, 4.8 and 4.9) for leaf type, growth habit and PPD all showed biomass was generally a positive linear function of DAS representing Phase II or the linear growth phase of the generalized growth curve. An obvious anomaly was the dip in Saskatoon in 2002 from 71 to 75 DAS which was due to two days of near 0 °C minimum temperatures, i.e., 0.4 °C on 64 DAS and 0.2 °C on 66 DAS, respectively, which stalled crop growth. The initial exponential growth phase (Phase I) was most evident in both locations in 2003 where the earliest biomass sampling were made on 30 and 37 DAS in Swift Current and 37 and 44 DAS in Saskatoon. Phase IV, representing crop senescence and maturation phase was captured only in Swift Current in 2004 showing a decline in biomass after maximum biomass (Phase III) where the latest reading across all location-years was made on 117 DAS.

4.3.4.1 Leaf Type Effects on Biomass Accumulation

Unifoliolate cultivars were usually superior to the fern cultivars in biomass accumulation early in the season but lost this advantage much later in the season (Fig. 4.7), similar to the response of leaf types to LI (Fig. 4.1). In both locations in 2003 and Saskatoon in 2004, differences between leaf-type response to biomass accumulation become non-significant later in the season but in Saskatoon in 2002 and Swift Current in 2004 and 2005, the fern-leafed cultivars showed significantly higher biomass than the unifoliolate cultivars. The earliest time that the fern-leafed cultivars showed significant biomass over the unifoliolate cultivars was 71 DAS in Saskatoon in 2002.

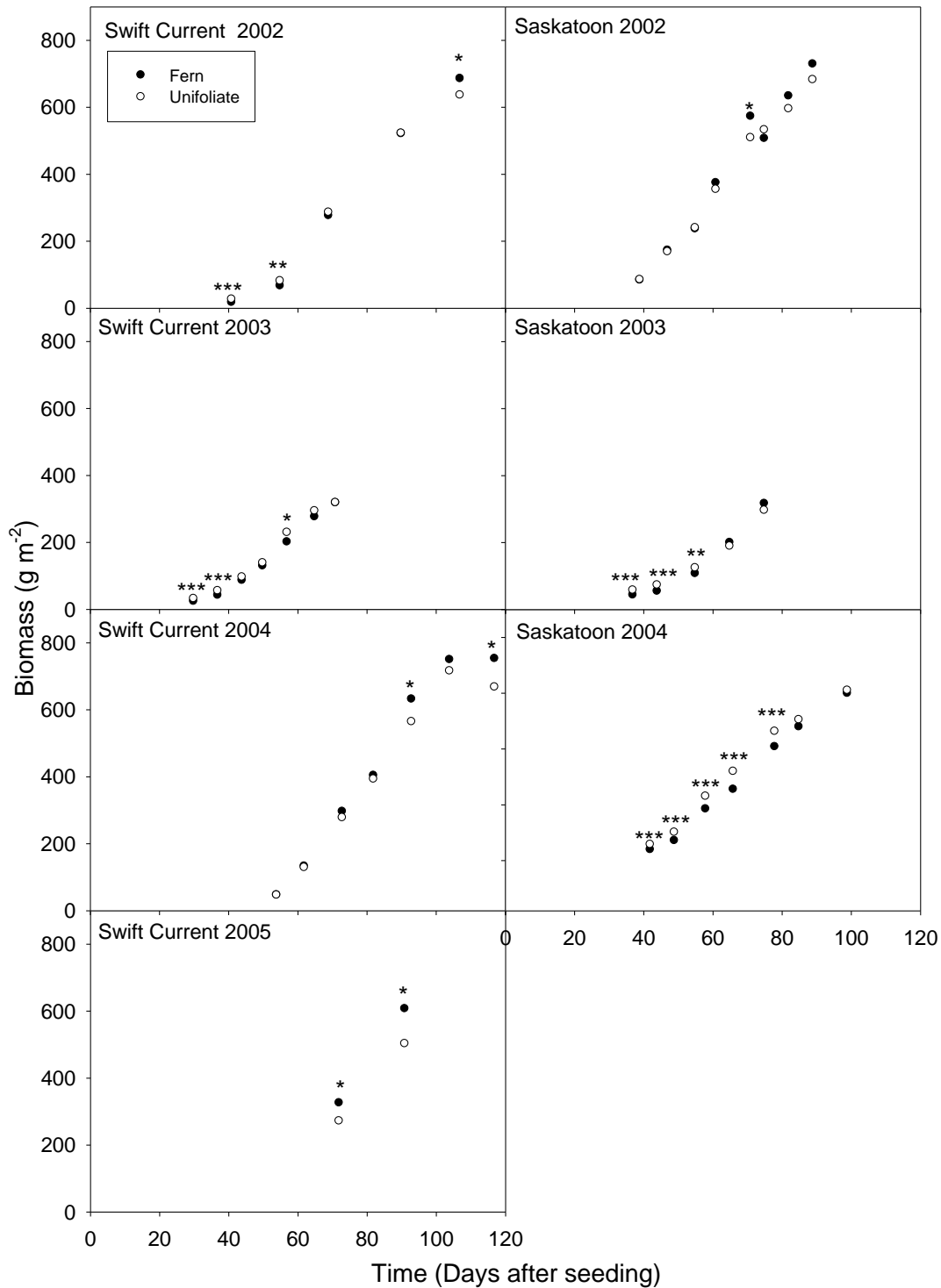


Fig. 4.7 Biomass accumulation of fern and unifoliolate leaf types in chickpea over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001 , respectively.

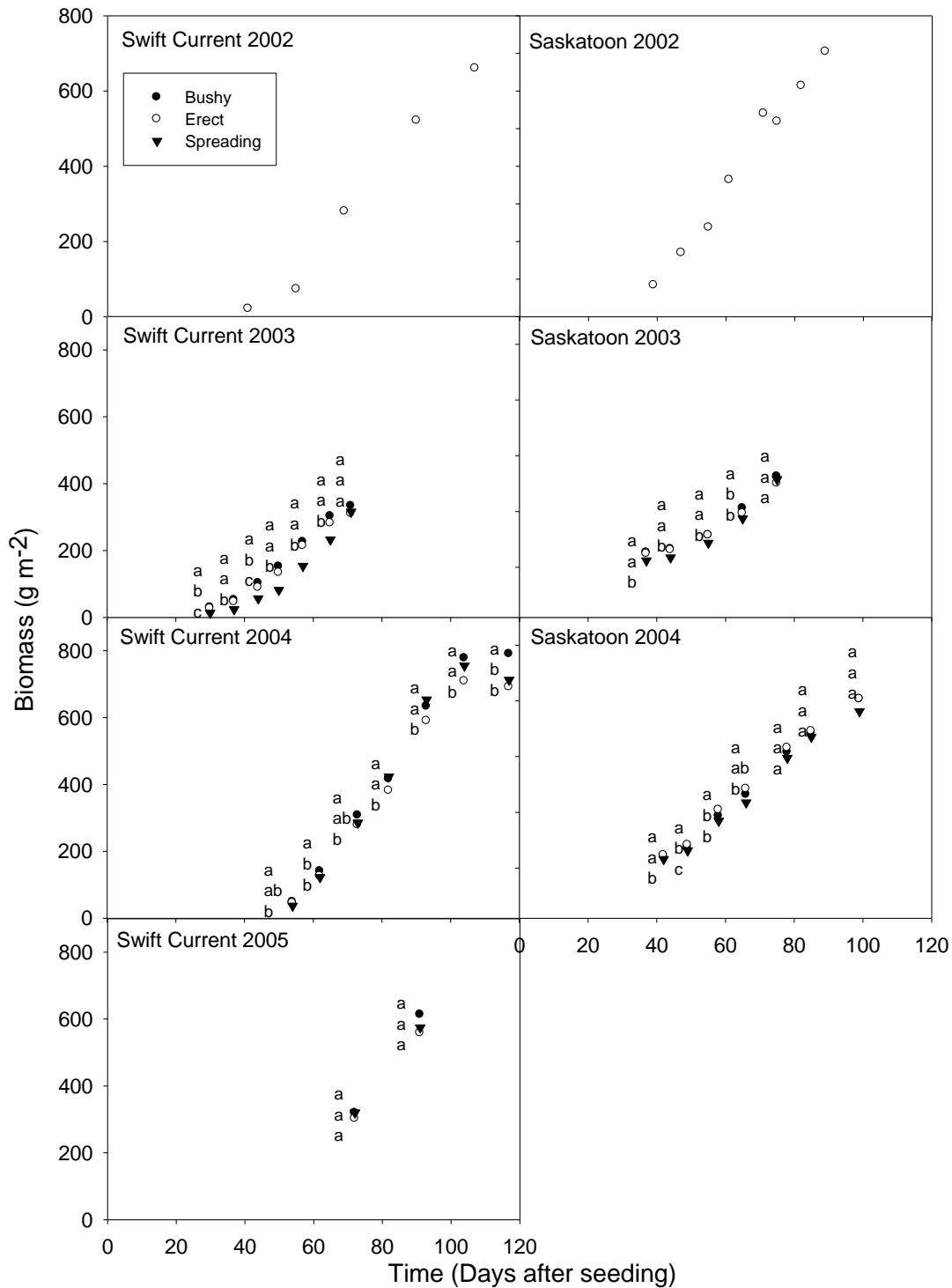


Fig 4.8 Biomass accumulation of bushy, erect and spreading growth habits in chickpea over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zones in 2002 and 2004. Data points represent treatment means of four replications. Means with same letter are not significantly different at $P < 0.05$.

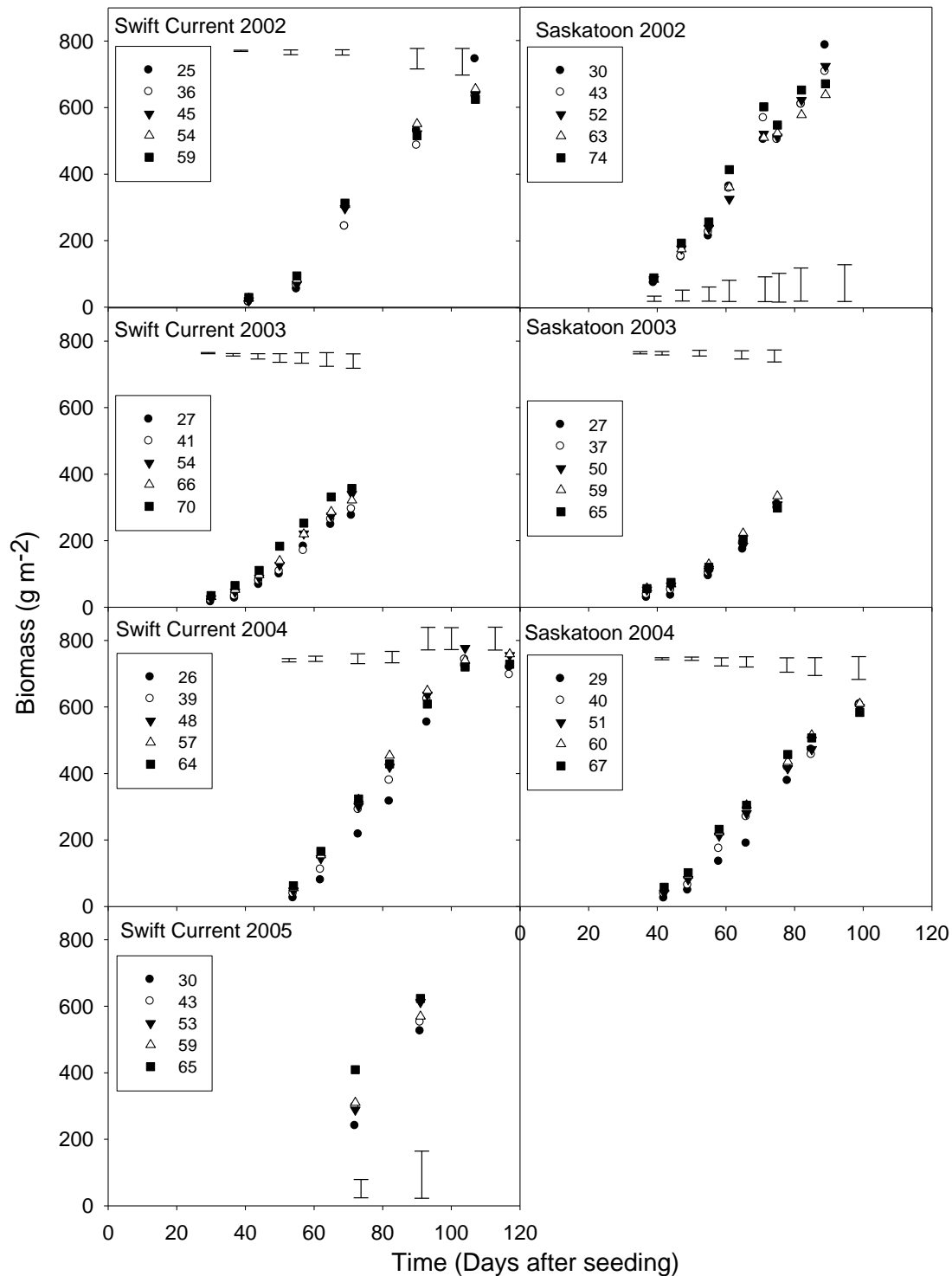


Fig. 4.9. Biomass accumulation at five chickpea plant population densities over the growing season in Swift Current in the Brown Soil zone from 2002 to 2005 and Saskatoon in the Dark Brown Soil zone from 2002 to 2004. Data points represent treatment means of four replications. Error bars indicate LSD for a sampling date.

The fern leaf type seems to have better biomass accumulation capacity by having significantly higher maximum biomass than the unifoliate types in three out of the seven location-years (Table 4.4). In the four location-years where differences were not significant, cultivars with fern leaves had higher maximum biomass in all but Saskatoon in 2004 where the unifoliate cultivars had higher maximum biomass. In Swift Current, fern-leafed cultivars had significantly higher maximum biomass than the unifoliate types in three location-years and similar maximum biomass in one location-year. In Saskatoon, leaf type did not, however, show any significant effect on maximum biomass.

4.3.4.2 Growth Habit Effects on Biomass Accumulation

The spreading cultivar tended to have significantly lower biomass accumulation than the bushy and erect cultivars on each DAS over the season in all location-years (Fig. 4.8). The short stature of the spreading cultivar may have contributed to its low biomass compared with the taller bushy and erect cultivars. The bushy cultivars tended to have significantly greater biomass than the erect cultivars in both locations in 2003 and Swift Current in 2004 but the situation was reversed in Saskatoon in 2004.

Considering all location-years from 2003 to 2005, the bushy cultivars had the greatest maximum biomass but the response of the erect and spreading was mixed (Table 4.4). The bushy cultivars had significantly higher maximum biomass in Swift Current in 2004, and shared significantly higher maximum biomass with the spreading cultivar in Swift Current in 2003. However, growth habits affected maximum biomass similarly in Saskatoon in 2003 and Swift Current in 2005.

Table 4.4 Effect of leaf type, growth habit and plant population density of chickpea cultivars on maximum biomass (g m^{-2}) over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

	Maximum biomass (g m^{-2})						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
<u>Leaf type</u>							
Fern	679a ^z	755a	337a	306a	818a	604a	590a
Unifoliate	634b	729a	336a	300a	771b	618a	503b
<u>Growth habit</u>							
Bushy			364a	314a	854a	624a	572a
Erect	657	742	326b	299a	772b	610a	561a
Spreading			328ab	307a	799b	550b	583a
<u>Target (plants m^{-2})</u>							
30	698	772	297†	298	777‡	629	518
45	634	740	310	293	814	591	565
60	651	749	349	310	852	612	590
75	663	690	342	321	799	609	573
85	647	747	383	301	778	601	595

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

4.3.4.3 Plant Population Density Effect on Biomass Accumulation

Despite actual PPD varying from location-year to location-year, biomass accumulation on a given DAS generally increased as PPD increased (Fig. 4.9). However, during the later part of the season, PPD effects on biomass became less pronounced or non-significant and no clear pattern was obvious across location-years. In both locations in 2002, the lowest PPDs attained the highest biomass at the last biomass sampling, a possible case of heightened indeterminate growth due to highest recorded August rainfall across all experiment years, offering most advantage to the sparse crop stand of the lowest PPD.

For each location-year, response of maximum biomass accumulated over the growing season to PPD was generally not significant (Table 4.4). No significant differences were noted in five out of seven location-years. In the two location-years where significant differences were noted, the differences between the highest and lowest maximum biomass accumulated were 30% in Swift Current in 2003 and 10% in Swift Current in 2004. A high level of compensation exists in chickpea which allows low PPD plants to grow extensively at the expense of available resources. At high PPD competition limited growth. The highest maximum biomass across treatments was 854 g m⁻² for the bushy cultivars in Swift Current in 2004 while the least maximum was 293 g m⁻² for 45 plants m⁻² target PPD in Saskatoon in 2003.

4.3.5 Radiation Use Efficiency

No significant differences in the response of RUE to growth habit were found in four location-years (Swift Current in 2002 and 2005 and Saskatoon in 2003 and 2004) as shown in Table 4.5. Unifoliolate cultivars had a significantly higher RUE (1.76 to 2.57 g MJ⁻¹) than the fern cultivars (1.62 to 2.33 g MJ⁻¹) in three location-years (Saskatoon in 2002 and Swift Current in 2003 and 2004). Growth habit had no significant effect on RUE in two location-years (Swift Current in 2003 and Swift Current in 2005) and the response of RUE to growth habit was mixed for the three remaining years.

Table 4.5 Effect of leaf type, growth habit and plant population density of chickpea cultivars on radiation use efficiency (g MJ^{-1}) over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

	Radiation Use Efficiency (g MJ^{-1})						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
<u>Leaf type</u>							
Fern	1.75a ^z	1.78b	1.38b	1.22a	2.33b	1.62a	1.64a
Unifoliate	1.70a	1.95a	1.51a	1.12a	2.57a	1.76a	1.97a
<u>Growth habit</u>							
Bushy			1.35a	1.11b	2.29b	1.61b	1.61a
Erect	1.72	1.86	1.45a	1.18b	2.43ab	1.69a	1.85a
Spreading			1.41a	1.44a	2.47a	1.63b	1.58a
<u>Target (plants m^{-2})</u>							
30	2.08†‡	1.90†	1.64†	1.42†‡	2.55†	1.76	1.89
45	1.73	2.08	1.44	1.23	2.43	1.71	2.00
60	1.65	1.86	1.35	1.02	2.46	1.62	1.83
75	1.64	1.71	1.34	1.21	2.33	1.61	1.65
85	1.59	1.80	1.34	1.14	2.16	1.55	1.32

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

RUE generally decreased with increasing PPD. In five location-years, lower PPDs resulted in significantly higher RUE than the higher PPDs. Two location-years showed no significant response in RUE to PPD, i.e., Saskatoon 2004 and Swift Current in 2005, although the same trend of decreasing RUE with increasing PPD was evident. In contrast, Solani et al. (2006) reported no response of RUE to PPD in a sub-humid temperate environment in New Zealand. Across all treatments, RUE ranged from 1.02 g MJ⁻¹ for the 60 plants m⁻² target PPD in Saskatoon in 2003 to 2.57 g MJ⁻¹ for the unifoliate leaf type in Swift Current in 2004, values which fall within the range of RUE reported in the review by Sinclair and Muchow (1999).

4.3.6 Spot vs. Continuous Light Interception Measurement

Data presented in Tables 4.6, 4.7 and 4.8 demonstrate the effect of leaf type, growth habit and PPD on maximum LI, maximum RI and RUE, respectively, as determined by spot and continuous measurements in Saskatoon in 2004 and Swift Current in 2005. Although the continuous measurements were taken for a reduced data set of four cultivars at 30, 60 and 85 plants m⁻² target PPD for three replications, the results were similar to that of the spot measurements taken for the total data set shown in Tables 4.2, 4.3 and 4.5. The results as determined by spot and continuous measurements were similar with respect to both response trends as well as magnitude but while no significant differences (depicted by mean errors for PPD) were noted between the two measurement types Swift Current in 2005, some differences were significant in Saskatoon in 2004. This observation could be attributed to the much later installation of the tube solarimeters in 2004 compared to 2005, i.e., 45 and 36 DAS, respectively, although variables were calculated for the same period for both measurement types in a given year. Another source of variation between the two measurement types could be due to the fact that continuous measurements were taken from a single position within a plot during the entire season whereas spot measurements were taken from different positions. Thomson and Siddique (1997) reported no differences in RUE determined by spot and continuous measurements for a single location-year data.

Table 4.6 Effect of leaf type, growth habit and plant population density (PPD) of chickpea cultivars on maximum light interception (%) as determined by spot and continuous measurements in Saskatoon (STN) in the Dark Brown Soil zone in 2004 and Swift Current (SC) in the Brown Soil zone in 2005.

	Light interception (%)			
	STN 2004		SC 2005	
	Spot ^y	Continuous	Spot ^y	Continuous
<u>Leaf type</u>				
Fern	91a ^z	86a	83a	81a
Unifoliate	81b	83b	61b	68b
<u>Growth habit</u>				
Bushy	89a	85a	81a	81a
Erect	81b	83a	61b	68b
Spreading	93a	89a	86a	81a
<u>Target (plants m⁻²)</u>				
30	87 (1.7)	84 (1.6)	72† (1.7)	72† (1.6)
60	89 (1.7)	85 (1.4)	79 (1.7)	78 (1.6)
85	87 (1.8)	87 (1.4)	81 (1.7)	83 (1.6)

^z Treatment means within a treatment column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test)

^y Results of reduced data set of four genotypes at three PPDs over three replications

Values in parenthesis indicate standard error of the mean for spot and continuous measurements in a given year

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

Table 4.7 Effect of leaf type, growth habit and plant population density (PPD) of chickpea cultivars on cumulative intercepted radiation (MJ m^{-2}) as determined by spot and continuous measurements in Saskatoon (STN) in the Dark Brown Soil zone in 2004 and Swift Current (SC) in the Brown Soil zone in 2005.

	Cumulative intercepted radiation (MJ m^{-2})			
	STN 2004		SC 2005	
	Spot ^y	Continuous	Spot ^y	Continuous
<u>Leaf type</u>				
Fern	364a ^z	295a	368a	355a
Unifoliate	342a	292a	258b	292b
<u>Growth habit</u>				
Bushy	366a	292a	367a	360a
Erect	342a	292a	258b	292b
Spreading	359a	303a	371a	346a
<u>Plant population density (plants m^{-2})</u>				
30	335† (10)	276† (7)	276† (16)	290† (21)
60	369 (10)	296 (7)	344 (16)	341 (21)
85	373 (9)	310 (7)	416 (16)	388 (21)

^z Treatment means within a treatment column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test)

^y Results of reduced data set of four genotypes at three PPDs over three replications

Values in parenthesis indicate standard error of the mean for spot and continuous measurements in a given year

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

Table 4.8 Effect of leaf type, growth habit and plant population density (PPD) of chickpea cultivars on radiation use efficiency (g MJ^{-1}) as determined by spot and continuous measurements in Saskatoon (STN) in the Dark Brown Soil zone in 2004 and Swift Current (SC) in the Brown Soil zone in 2005.

	Radiation use efficiency (g MJ^{-1})			
	STN 2004		SC 2005	
	Spot ^y	Continuous	Spot ^y	Continuous
<u>Leaf type</u>				
Fern	1.64a ^z	2.23a	1.34a	1.70a
Unifoliate	1.54a	1.71b	2.01a	1.80a
<u>Growth habit</u>				
Bushy	1.63a	2.18a	1.37a	1.69a
Erect	1.54a	1.71a	2.01a	1.80a
Spreading	1.65a	2.37a	1.27a	1.73a
<u>Plant population density (plants m^{-2})</u>				
30	1.80† (0.16)	2.55† (0.35)	1.80 (0.38)	1.99a(0.41)
60	1.57 (0.15)	2.02 (0.35)	1.58 (0.38)	1.99 (0.41)
85	1.39 (0.16)	1.64 (0.36)	1.61 (0.43)	1.20 (0.41)

^z Treatment means within a treatment column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test)

^y Results of reduced data set of four genotypes at three PPDs over three replications

Values in parenthesis indicate standard error of the mean for spot and continuous measurements in a given year

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

4.3.7 Seed Yield

Significant differences were observed in the response of seed yield to the main effects of leaf type, growth habit and PPD in all location-years (Table 4.9). Fern-leaved cultivars had significantly higher seed yield than the unifoliate cultivars in all location-years. The highest seed yield was produced by the fern cultivars in Swift Current in 2004 (369 g m^{-2}) while the lowest yield was produced by the unifoliate cultivars in Saskatoon in 2004 (96 g m^{-2}).

The bushy cultivars also showed significantly higher seed yield in all five location-years, sharing this superiority with the spreading cultivar in two location-years, both in Saskatoon in 2003 and 2004. The erect cultivars had significantly lower seed yield in all five location-years, sharing this with the spreading cultivar in one-location-year. The highest seed yield was produced by the bushy cultivars in Swift Current in 2004 (370 g m^{-2}) while the spreading cultivar produced the lowest yield in Swift Current in 2003.

Generally, seed yield increased in response to increasing PPD. The 75 plants m^{-2} target PPD (56 plants m^{-2} actual PPD) produced the highest yield in Swift Current in 2004 (346 g m^{-2}) while the lowest target PPD (27 plants m^{-2} actual PPD) produced the lowest yield in Swift Current in 2003 (116 g m^{-2}).

4.3.8 Harvest Index

Harvest index was significantly higher for fern-leaved cultivars (0.33 to 0.53) than the unifoliate cultivars (0.20 to 0.35) in all location-years (Table 4.10). The bushy and spreading cultivars had comparable HI (0.38 to 0.50 and 0.43 to 0.53, respectively) and were therefore more efficient at biomass partitioning to seed yield than the erect cultivars having significantly lower HI (0.31 to 0.45) in all location-years. PPD did not generally have any significant effect on HI. Harvest index was not significantly affected by PPD in five out of seven location-years (both locations in 2002, Saskatoon in 2003 and 2004 and Swift Current in 2005). However, in the two location-years where significant differences

Table 4.9 Effect of leaf type, growth habit and plant population density of chickpea cultivars on seed yield (g m^{-2}) over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

	Seed yield (g m^{-2})							
	2002		2003		2004		2005	
	SC	STN	SC	STN	SC	STN	SC	
<u>Leaf type</u>								
Fern	267a ^z	173a	136a	154a	369a	209a	210a	
Unifoliolate	162b	110b	107b	108b	191b	96b	118b	
<u>Growth habit</u>								
Bushy			142a	152a	370a	217a	208a	
Erect	212	142	123b	132b	282c	145b	163c	
Spreading			118b	155a	353b	219a	228b	
<u>Target (plants m^{-2})</u>								
30	163†‡	119†	116†	128	276†‡	160†	175†	
45	204	136	130	148	324	177	187	
60	217	133	128	137	335	185	189	
75	241	153	130	150	346	180	191	
85	239	161	136	136	339	196	196	

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

Table 4.10 Effect of leaf type, growth habit and plant population density of chickpea cultivars on harvest index over five location-years in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

	Harvest index						
	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
<u>Leaf type</u>							
Fern	0.33a ^z	0.34a	0.53a	0.47a	0.51a	0.41a	0.44a
Unifoliate	0.27b	0.23b	0.35b	0.30b	0.32b	0.20b	0.30b
<u>Growth habit</u>							
Bushy			0.50b	0.50a	0.50a	0.38b	0.45a
Erect	0.30	0.29	0.45c	0.37c	0.42b	0.31c	0.37c
Spreading			0.53a	0.46b	0.51a	0.47a	0.43b
<u>Target (plants m⁻²)</u>							
30	0.29	0.27	0.49†	0.41	0.43†‡	0.34	0.41
45	0.32	0.29	0.49	0.43	0.45	0.36	0.41
60	0.31	0.27	0.47	0.43	0.48	0.37	0.40
75	0.33	0.29	0.46	0.41	0.46	0.34	0.41
85	0.27	0.31	0.46	0.43	0.48	0.37	0.40

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

† Actual plant population density showed a significant linear response ($P < 0.05$)

‡ Actual plant population density showed a significant quadratic response ($P < 0.05$)

were observed, one tended to show a decreasing pattern in HI with increasing PPD i.e. in Swift Current in 2003, while the other showed the reverse trend of increasing HI with increasing PPD i.e. in Swift Current in 2004. The lack of response of HI to PPD implies that increasing PPD will not confer any disadvantage on HI.

Harvest index was generally higher in Swift Current than in Saskatoon in all location-years. Lower HI values were noted at both locations in 2002 as opposed to 2003 which had the lowest values for all other variables studied. This observation was likely due to above average late rains in August of 2002 in both locations, thus intensifying indeterminate growth in chickpea by producing a burst of new vegetative growth which led to a lowering of HI. Siddique et al. (1984) attributed low HI of chickpea crop at high PPD to low HI of branches that appeared late in the season. Harvest index ranged from 0.20 to 0.53, with the lowest value for the unifoliolate cultivars in Saskatoon in 2004 and the highest value for both the fern and spreading cultivars in Swift Current in 2003.

4.3.9 Correlation of Seed Yield with Growth and Yield Parameters

Pearson correlation coefficients were determined for seed yield and the other parameters assessed (Table 4.11) to establish any associations between seed yield and growth parameters. A fairly consistent pattern of correlation was found across location-years between seed yield and each parameter tested. Harvest index showed the most consistent and strongest significant positive correlation with seed yield in all location-years, followed by maximum LI which also showed significant positive correlation in all but one location-year, i.e., Saskatoon in 2004. Maximum RI showed positive significant correlations in all location-years except in Saskatoon in 2004 where the correlation was negative. Decreased seed yield with increasing maximum RI in the Saskatoon in 2004 may be the result of a wet and cool season coupled with inclement end of season weather consisting of late rains, early frost and snow. Maximum biomass was significantly and positively correlated with seed yield in five location-years but was not significantly correlated with seed yield in Swift Current in 2002 and Saskatoon in 2004. Radiation use efficiency showed no correlation with seed yield in five location-years but significantly

Table 4.11 Pearson correlation coefficients (r) for chickpea seed yield and growth parameters in Swift Current (SC) in the Brown Soil zone from 2002 to 2005 and Saskatoon (STN) in the Dark Brown Soil zone from 2002 to 2004.

Location-year	PPD (plants m ⁻²)	Maximum LI (%)	Maximum RI (MJ m ⁻²)	Maximum Biomass (g m ⁻²)	RUE (g MJ ⁻¹)	HI
SC 2002	0.21	0.57***	0.49***	0.21	-0.20	0.39***
SC 2003	0.16	0.39***	0.45***	0.35***	-0.10	0.54***
SC 2004	0.49***	0.71***	0.64***	0.25***	-0.37***	0.88***
SC 2005	0.08	0.61***	0.61***	0.42***	-0.04	0.86***
STN 2002	0.15	0.49***	0.47***	0.32**	-0.26*	0.66***
STN 2003	0.03	0.36***	0.19*	0.36***	0.11	0.53***
STN 2004	-0.01	0.01	-0.22*	0.04	0.13	0.87***

*, ** and *** indicate significant difference at P < 0.05, 0.01 and 0.001, respectively.

HI Harvest index PPD Plant population density
 Biomass RI Cumulative intercepted radiation
 LI Light interception RUE Radiation use efficiency

and negatively correlated with seed yield in two location-years. Seed yield showed no significant correlation with PPD in six out of seven location-years, but a significant positive correlation was found in the highest yielding location-year, i.e., Swift Current in 2004.

4.4 DISCUSSION

Chickpea grown in the short season of the Canadian Prairies, an environment quite different from traditional chickpea producing areas of the world, were assessed for LI, RI, biomass, RUE, seed yield and HI in cultivars with varying canopy types. The varying canopy types were fern and unifoliate leaves and bushy, erect and spreading growth habits at target PPDs of 30, 45, 60, 75 and 85 plants m⁻². The aim of this research was to identify traits that best utilize the limited resources in this environment in order to maximize seed yield.

4.4.1 Leaf Types

Cultivars with fern leaves were superior to the unifoliate cultivars with respect to maximum LI, seed yield and HI in all location-years. The fern cultivars also had significantly higher maximum RI, except for 2003 (Table 4.3) and maximum biomass was significantly higher for the fern cultivars only in Swift Current (Table 4.4). No consistent response of RUE to leaf type was noted i.e. both leaf types had similar RUE in four location-years but the unifoliate cultivars were superior in three location-years (Table 4.5). This is similar to the findings of Li et al. (2006) who reported higher HI and seed yield of kabuli chickpea cultivars with fern leaves than cultivars with unifoliate leaves but no biomass differences between leaf types in the Northern Great Plains. Li et al. (2006) ascribed the higher HI of the fern cultivars to a larger leaf surface area in fern leaves than unifoliate leaves which allows more photosynthate translocation to subtending pods.

The rate of photosynthesis of a leaf depends partly on the available light (Ludlow and Wilson, 1971; Prioul and Bourdu, 1973) and PAR attenuates with depth within a canopy (Szeicz et al. 1964, Allen and Brown, 1965 and Anderson, 1969). The pinnate nature of the fern leaves in addition to the erectophile leaf orientation may allow better light penetration into the canopy even at full canopy. In contrast, lower leaves of the unifoliate canopy may receive less light due to the shading effect of the semi-dissected lamina structure and planophile orientation of the unifoliate leaves. Photosynthesis of lower leaves in the fern canopy may therefore add a continuous supply of photosynthate to fill pods to contribute to higher seed yield and HI advantage over the unifoliate canopy.

Beuerlein et al. (1971) reported seed yield increases in debranched soybean (*Glycine max* (L.) Merr.) plants at high PPD and ascribed this to greater light penetration at flowering which resulted in higher HI and leaf efficiency i.e. seed yield per unit leaf area. Reta-Sánchez and Fowler (2002) demonstrated that modifying leaf shape to increase light penetration into cotton (*Gossypium hirsutum* L.) canopy increased seed yield by 34%.

Early vigor is a highly desired trait in short-season production systems as it affords added advantages of rapid plant growth and early canopy closure to maximize seasonal light interception, reduction of evaporative water loss from the soil surface and limits weed growth. In this research, LI was an indication of canopy coverage as a percentage, 100% being the maximum. Although the fern cultivars attained greater maximum LI, RI and biomass, the time-course graphs of LI, seasonal RI and biomass (Figs 4.1, 4.4 and 4.7, which depicted relative advantages of the different leaf types at various stages during the growing season), revealed that the unifoliate cultivars had an early advantage up to at least mid-season. Early vigor fern cultivars may be achieved through larger seed size (Sabaghpour et al. 2003) or larger embryo size (Lopez-Castaneda et al., 1996) as seen in temperate cereals. Sabaghpour et al. (2003) reported an association between chickpea 100 seed-weight and early vigor.

Small seed size could reduce chickpea production costs by \$31 to \$52 ha⁻¹ (Gan et al., 2003c). However, Gan et al. (2003d) demonstrated through path analysis that seed yield in chickpea on the Canadian Prairies principally depended on seed weight together with pods m⁻². Rao (1996) reported the substantial contribution of seed weight to seed yield in large seeded chickpea. Gan et al. (2003a) also reported higher percent plant establishment for the larger-seeded kabuli cultivars than small-seeded desi cultivar i.e. 90 to 72% vs. 81 to 69%, respectively. Recently, Australian researchers have been improving wheat (*Triticum aestivum* L.) seed yield through early vigor (Botwright et al. 2002, Rebetzke et al., 2004, Rebetzke et al., 2007). Early vigor fern cultivars could help boost the yield potential of short-season chickpea through early maturity (Sabaghpour et al. 2003; Gupta, 1985 and Singh et al., 1997), another highly desired trait on the Canadian Prairies, and better stand establishment (van der Maesen, 1972).

4.4.2 Growth Habit

Cultivars with the bushy growth habit consistently performed better than the erect cultivars for seed yield and HI in all location-years. The bushy cultivars also showed significantly higher maximum LI and maximum RI than the erect cultivars in Swift Current but differences were not significant in Saskatoon (Tables 4.2 and 4.3). While no obvious advantage of early canopy closure was exhibited by any of the growth habits, probably due to the row spacing being too wide for a short growing season, the bushy cultivars tended to have greater canopy coverage as indicated by LI and biomass accumulation over the growing season (Figs 4.2 and 4.5) which may have contributed to greater seed yield and HI.

This greater productivity of the bushy over erect cultivars agrees with Rubio et al. (2004) who reported greater seed yield of chickpea lines with bushy growth habit than erect habit lines, and attributed it to more primary and secondary branching resulting in a higher number of reproductive nodes in the bushy habit lines. Walton (1991) reported a significant positive correlation between number of reproductive nodes and seed yield in field pea (*Pisum sativum* L.) in the dry, short-season Mediterranean type climate of Western Australia. A debranched chickpea crop derived from removal of branches produced higher seed yield through an increase in apical branches, which bore a higher number of reproductive nodes, as compared with the freely branching control (Siddique and Sedgley, 1985).

The overall performance of the spreading cultivar was intermediate between the bushy and erect cultivars regarding maximum LI, seed yield and HI (Tables 4.2, 4.9 and 4.10). The spreading cultivar is highly branched similar to the bushy cultivars, so the average performance of the spreading cultivar could be explained on the basis of its shorter stature (Table 3.7) resulting in fewer reproductive nodes, lower seed yields and lower HI as compared with the taller bushy cultivars.

Seasonal RI was significantly higher for the bushy cultivars than either the erect or spreading cultivars but was similar for the erect and spreading cultivars (Table 4.3). Seasonal RI therefore seems to be maximized by the use of bushy cultivars. The bushy cultivars also produced higher maximum biomass than either the erect or spreading cultivars but between the erect and

spreading cultivars, the response was mixed (Table 4.4). Response of RUE to growth habit was, however, not significantly different in two out of five location-years and mixed for the three remaining location-years (Table 4.5). Within species, RUE is a fairly conservative value, but reduction in RUE due to moisture stress is well documented (Hughes et al, 1987; Thomson and Siddique, 1997; Sinclair and Muchow, 1999; Tesfaye et al. 2006). The lack of differences with respect to growth habit is therefore not surprising and the lowest RUE values were obtained in the drought year.

The results of this research partly agree with Hughes et al. (1987) who also reported similar RI for the erect and prostrate growth habits while the erect growth habit had higher RUE than the prostrate types. However, Hughes et al. (1987) seeded most erect lines at higher PPD i.e. 60 plants m⁻² while all the prostrate lines were seeded at 30 plants m⁻² therefore growth habit was confounded with PPD.

4.4.3 Plant Population Density

Despite maximum LI and maximum biomass tending to remain fairly constant with increasing PPD, the time-course graphs of LI and biomass accumulation (Figs 4.3 and 4.9) as well as that of maximum seasonal RI (Fig 4.6) showed a general increasing trend in response to increasing PPD on each sampling date. Maximum RI also showed a clear increasing trend with increasing PPD (Table 4.3). High PPD canopies therefore captured more light over the growing season, resulting in an increase in biomass accumulation and higher seed yield. Generally, HI remained constant with increasing PPD across location-years (Table 4.10), although RUE generally decreased as PPD increased (Table 4.5), while seed yield was usually increased by increasing PPD (Table 4.9).

Hughes et al. (1987) also found chickpea canopy at 60 plants m⁻² to have higher RI but used light less efficiently for conversion to biomass compared to a PPD of 30 plants m⁻². A stable HI with increasing PPD (Ball et al., 2000) but decreasing RUE with increasing PPD in short-season soybean (Purcell et al., 2002) have also been reported. Purcell et al. (2002) speculated that higher lower-leaf senescence due to greater light attenuation at higher PPD and water and nutrient stress may be the cause of decreasing RUE at higher PPDs. Also, at high PPDs proportionately less intercepted radiation goes into total biomass to maintain the proportions of starch, proteins and

oils in soybean. Another factor that may play a role is the fact that more light is intercepted by the dense canopy at high PPDs but it is normally associated with greater mutual shading of lower leaves depending on canopy architecture factors such as leaf number, area, shape and orientation and steadily increasing fruit load as the season progresses. Less intercepted light is thus available for new biomass production in addition to both the maintenance of a larger canopy and the diversion of assimilate to seeds in an indeterminate crop.

4.4.4 Seed Yield Associations

A significant and positive correlation between seed yield and maximum LI, RI, maximum biomass and HI was obtained for chickpea grown in the temperate short-season production system of the Canadian Prairies. This finding is supported by a number of studies on, e.g., correlation between both HI and biomass with seed yield have been reported by Saxena et al. (1990), Silim and Saxena (1993), Rao (1996), Ayaz et al. (2004b) and Toker and Cagirgan (2004). Harvest index showed the strongest correlation with seed yield. Striking increases in yield of grain crops are commonly attributed in part to improved HI. For example, HI in cool season cereals has increased from 0.35 to 0.50 in wheat (Austin et al., 1980) and 0.36 to 0.48 in barley (*Hordium vulgare* L.) (Riggs et al., 1981). In chickpea, HI values reported in recent studies show a wide range of variation e.g. 0.30 to 0.63 (Ayaz et al., 2004b), 0.15 to 0.51 (Li et al., 2006) and 0.17 to 0.36 (Tesfaye et al., 2006). Harvest index ranged from 0.20 to 0.53 in this research and the least HI values were noted in 2002 which was the year with the greatest end-of-season precipitation. The low HI values were therefore, a result of heightened indeterminacy. Gains in seed yield in chickpea could be improved by increasing and stabilizing HI possibly through early maturity, which would reduce the impact of indeterminacy caused by late rains.

Accumulation of intercepted light over the growing season is important to biomass production, which is subsequently partitioned to seed yield. Production of a large biomass as a result of high LI is fundamental to biomass production across different environments and crops. This relationship has been demonstrated for barley, potatoes, sugar beet and apples (Monteith, 1977) and for cereals (Gallagher and Biscoe, 1978), in the U.K. Similar results were reported for six grain legumes including chickpea in the Mediterranean-type environment of southwestern Australia (Thomson and Siddique, 1997). Maximum canopy LI ranged from 59 to 91% in this

research. Increasing LI by exploring a more isodiametric crop arrangement or by identifying the intra- and inter-row spacing of the different canopy types that maximizes LI may lead to seed yield improvement. Halving inter-row spacing while maintaining intra-row spacing in chickpea increased radiation interception by about 30% (Leach and Beech, 1988). Saccardo and Calcagno (1990) recommended 0.40, 0.25 and 0.12 inter-row spacing at 0.10 m intra-row spacing for semi-prostrate, semi-erect and erect chickpea cultivars at PPDs of 24, 40 and 80 plants m⁻², respectively, under the Mediterranean conditions of Italy.

No correlation was found between seed yield and maximum LI in Saskatoon in 2004 and with maximum biomass in Swift Current in 2002 and Saskatoon in 2004 (Table 4.11). These two environments were particularly challenging in that rainfall in Swift Current in 2002 was excessive, i.e., 70% over the long-term average and late seeding coupled with cool temperatures and early frost in Saskatoon in 2004 may have contributed to this result.

Radiation use efficiency was constant for four out of seven location-years regarding leaf type. The product of RUE and seasonal RI results in seasonal biomass accumulation. Therefore, a constant RUE implies that seasonal RI would have to be increased in order to increase biomass accumulation for subsequent partitioning to seed yield. Seed yield is the direct product of HI which depends on seasonal biomass accumulation.

Plant population density showed a significant positive correlation with seed yield in only one out of seven location-years (Table 4.11). However, Gan et al. (2003d) found a significant positive correlation between PPD and seed yield for both desi and kabuli chickpea grown on conventional fallow and on no-till wheat stubble. This may be due to the fact that a narrower range of PPDs (20 to 50 plants m⁻²) was studied by Gan et al. (2003d), thus the linear response of seed yield to PPD resulted in a significant positive linear correlation. In this research, actual PPDs ranged from 25 to 74 plants m⁻² (Table 3.4) and increases in seed yield with PPD tapered, especially at the two highest PPD treatments in all location-years. The response of seed yield to PPD was therefore curvilinear (Figs. 3.1, 3.2 and 3.3) and thus correlation across the PPD range was not significant for a linear association.

Overall, the variables that were significantly and positively correlated with seed yield, i.e., LI, RI, biomass and HI were also generally significantly higher for the cultivars with fern leaves and bushy growth habit. Light interception, RI and biomass also generally increased as PPD increased. Harvest index however, remained fairly constant as PPD increased, indicating that increasing PPD would not be detrimental to the harvested seed yield. This research therefore suggests that the chickpea ideotype for the Canadian Prairies would have fern leaves and a bushy growth habit. Higher PPD than currently recommended or a change in row space configuration would also be required to enable greater maximum LI and biomass production for efficient partitioning to seed yield.

5.0 Effect of Canopy Architecture and Plant Population Density on Water Use Efficiency in Chickpea (*Cicer arietinum* L.)

5.1 INTRODUCTION

Chickpea (*Cicer arietinum* L.) is the third most important pulse crop regarding global production, after dry bean (*Phaseolus vulgaris* L.) and field pea (*Pisum sativum* L.). Chickpea is also the third most important pulse crop in Western Canada regarding production and exports after field pea and lentil (*Lens culinaris* Medik.). Chickpea and other pulses are used in rotation with canola in the cereal-based crop production system of the Canadian Prairies. Low and variable rainfall are frequently the main factors limiting crop yield on the Prairies (Cutforth et al., 1999) and dryland cropping systems in general. Crop production on the Canadian Prairies is further challenged by a short growing season of no more than 120 days (May to August). Crops with high water use efficiency (WUE) i.e., amount of crop biomass or seed yield per unit water use (WU), will be at an advantage in such environments (Passioura, 1977; Ludlow and Muchow, 1990; Hatfield et al., 2001).

Passioura (1977) related crop seed yield to WUE and WU under limited water supply as

$$\text{Yield} = \text{WU} \times \text{WUE} \times \text{HI} \quad [5.1]$$

where WU or evapotranspiration (ET) is the water use via plant transpiration (T) and direct evaporation from soil surface (E_s), WUE is WUE based on biomass, i.e., ($\text{WUE}_{\text{biomass}}$) and HI is harvest index, i.e., seed yield divided by total seasonal biomass. Water use efficiency based on seed yield (WUE_{seed}) which is seed yield divided by seasonal WU is also reported in the literature and it serves as an adequate comparator where biomass data are unavailable. In drought-prone environments, improving one or more of the three yield parameters in equation 5.1, either through breeding or agronomic practices may increase seed yield (Passioura, 1977).

Richards et al. (2002) showed that $\text{WUE}_{\text{biomass}}$ could be improved by decreasing E_s or increasing T based on the equation

$$\text{WUE}_{\text{biomass}} = \frac{\text{TE}}{1 + E_s/T} \quad [5.2]$$

where TE is transpiration efficiency i.e. efficiency of biomass production per unit water transpired. Crops depending on stored moisture improve WUE through TE while crops using in-season precipitation improve WUE effectively by decreasing E_s (Richards et al. 2002). On the Canadian Prairies, up to two-thirds of annual precipitation falls within the growing season from May to August (Longley, 1972; Dey, 1982).

Management of canopy development is required for optimal biomass levels for maximal HI (Siddique and Sedgley, 1987; Beech and Leach, 1989). The rate of canopy development is a combination of leaf type, growth habit, plant population density (PPD) and spacing. Chickpea canopies with differing rates of canopy development may affect crop WU, biomass accumulation and WUE. Commercial cultivars of chickpea available in Saskatchewan are characterized by two leaf types, namely, unifoliolate and fern. The cultivars also exhibit three growth habits namely, bushy, erect and spreading. Leaf type and growth habit in chickpea are each controlled by single Mendelian genes (Muehlbauer and Singh, 1987). The current recommended PPD for chickpea on the Canadian Prairies is 44 plants m^{-2} based on preliminary studies (Saskatchewan Pulse Growers, 2000) and a study involving a narrow agronomic range of 20 to 50 plants m^{-2} and four cultivars in the Brown Soil zone (Gan et al., 2003a).

Crops that do not rapidly develop leaf area early in the season tend to lose available soil moisture to soil evaporation. More water is used in crop T by increased crop vigor through high PPD, large seed size, root nutrition and improved seedling establishment (Richards, 2002). However, increased pre-anthesis WU may offset any seed yield gains due to lack of moisture during grain fill (Angus and van Herwaarden, 2001). On the Prairies, a strategy of high WU before anthesis may be better to maximize seed yield because of the short growing season and the indeterminate habit of chickpea. Chickpea grown at high PPD and narrow rows in Australia enhanced WU and seed yield, outweighing increased water depletion (Leach and Beech, 1988; Beech and Leach, 1989).

Alvino and Leone (1993) studied the response of different pea leaf types to high and low moisture stress and found significant differences in WU at high moisture stress but no differences when moisture was not limiting. Li et al. (2006) reported higher crop growth rate (CGR) for fern-leafed than unifoliate-leafed cultivars but no PPD effect in a study of kabuli chickpea cultivars in the Brown Soil and Dark Brown Soil zones of the Canadian Prairies. Richards (1991) proposed genetic improvement of WUE through an increase in T relative to E_s by selecting for prostrate growth habit or higher biomass in temperate crops such as wheat (*Triticum aestivum* L.). In Syria, prostrate-spreading chickpea was found to increase WUE compared to erect forms, although growth habit and phenology were confounded (ICARDA, 1982).

Information on the effect of varying chickpea canopy types on early crop development, WU and WUE on the Canadian Prairies is generally lacking. The hypothesis of this current experiment was that canopy traits, i.e., leaf type and growth habit, together with PPD which contribute to early and/or greater canopy development would increase seed yield and WUE. The objective of this current experiment was to assess the adaptation of chickpea cultivars to the Canadian Prairies by determining the effects of varying chickpea canopy traits (leaf type and growth habit) and PPD on the parameters of the Passioura (1977) equation i.e. equation 5.1, namely seed yield, WUE, WU and HI.

5.2 MATERIALS AND METHODS

5.2.1 Experimental Design

Experiments were conducted over six location-years involving two locations per year from 2003 to 2005 (Table 5.1). Locations seeded were University of Saskatchewan Goodale Experimental Farm (2003, 2004 and 2005) and Saskatchewan Pulse Growers (SPG) Land (2003 and 2004), both within a 30-km radius of Saskatoon, SK (52° 7' N, 106° 37' W) in the Dark Brown Soil zone. A third location was at the Agriculture and Agri-Food Canada Research Centre (2005) near Swift Current, SK (50° 16' N, 107° 47' W) in the Brown Soil zone. The soil type at Goodale and SPG was Dark Brown Chernozem (Typic Borolls) while soil type at Swift Current was an Orthic Brown Chernozem (Aridic Haploboroll) - Swinton silty loam. In all years, the previous rotations were under chemical fallow in the drier Brown Soil zone fields whereas the moister Dark Brown Soil fields were under wheat.

Six chickpea cultivars available to farmers in Saskatchewan with varying combinations of leaf type and growth habit were seeded over the three experiment years (Table 5.2). Plots were overseeded by 15% in order to achieve target PPDs of 45 and 75 plants m⁻², for evaluation of crop performance at the recommended PPD vs. high PPD, respectively. For each location-year, the experimental design was a randomized complete block design with a factorial combination of cultivar and PPD and treatment combinations were replicated four times. Row spacing was maintained at 0.31 m for all six location-years. Seeding date, plot size and number of rows were as presented in Table 5.1.

Table 5.1 Seeding date, harvest date, plot size and number of rows over six location-years at Goodale (2003 to 2005), SPG (2003 and 2004) and Swift Current (2005).

	2003		2004		2005	
	Goodale	SPG	Goodale	SPG ^z	Goodale	Swift Current
Seeding date	May 14	May 20	May 25	June 5	May 11	May 9
Harvest date	Sep 1	Sep 1	Nov 10	Nov 11	Oct 11	Sep 21
Plot size (m)	1.2 x 3.7	1.2 x 3.7	4.8 x 3.6	4.8 x 3.6	4.8 x 3.6	4.9 x 4.9
Rows	4	4	16	16	16	16

^z Excluded from analysis due to extreme late seeding and early frost

Table 5.2 Leaf type, growth habit and seed class of chickpea cultivars grown over six location-years at Goodale (2003 to 2005), SPG (2003 and 2004) and Swift Current (2005).

Cultivar	Leaf type	Growth habit	Seed class
CDC Ebony	Fern	Spreading	Desi
CDC Anna	Fern	<i>Bushy</i>	Desi
CDC Cabri	Fern	Bushy	Desi
CDC ChicChi	Fern	Bushy	Kabuli
Myles	Fern	Erect	Desi
Evans	Unifoliate	Erect	Kabuli

A mixture of carbathiin and thiabendazole (Crown) at 600 ml 100 kg⁻¹ seed and metalaxyl (Apron) at 16 ml 100 kg⁻¹ seed was used as a pre-seeding treatment against seed-borne diseases. Seeding depth was 50 mm in all location-years and seeds were inoculated with 5.5 kg ha⁻¹ of granular *Rhizobium* inoculant, Nodulator® (Becker Underwood Inc, Saskatoon, SK) within the seed row for symbiotic N fixation. Ascochyta blight was controlled at Goodale and SPG by chlorothalonil (Bravo) at 3.20 L ha⁻¹ applied at first flower, followed by two applications of pyraclostrobin (Headline) at 0.40 L ha⁻¹ at 10-day intervals. At Swift Current four fungicide applications, including two applications each of Headline at 0.40 L ha⁻¹ and Bravo at 4.0 L ha⁻¹, were used for ascochyta blight control.

Control of weeds at Goodale and SPG involved spring application of ethalfluralin (Granular Edge) at 28.0 kg ha⁻¹ and pre-emergence application of imazethapyr (Pursuit) at 0.07 L ha⁻¹. Weeds were controlled at Swift Current using a pre-seeding application of Granular Edge at 17.0 kg ha⁻¹, a pre-emergence application of glyphosate (Roundup) at 2.50 L ha⁻¹, imazethapyr at 0.03 L ha⁻¹ and a post-emergence application of sethoxydim (Poast Ultra) at 0.48 L ha⁻¹. Grasshopper incidence at Goodale in 2003 and 2004 and SPG in 2003 was controlled by spraying chlorpyrifos (Lorsban) at early flowering and mid-pod fill at 1.0 L ha⁻¹.

5.2.2 Data Collection and Calculations

Stand counts were determined at about the 4-node stage from two or three randomly selected 1m sections of three different rows per plot. From the 6-node stage until physiological maturity, biomass was cut at ground level from a bordered area of 0.31m² (0.25 m across four rows) per plot at approximately 7 to 14-day intervals, depending on weather conditions. Crop growth rate was then calculated up to maximum biomass as the difference between two consecutive biomass samplings divided by the corresponding number of days between the biomass samplings.

At harvest maturity, six plants were harvested, dried at 40 °C for about a week and weighed, after which the plants were threshed and the seeds weighed. Harvest index was then calculated as the quotient of the seed and total plant weights. Plots were combined at harvest maturity and the seed air-dried at 40 °C for seven days to obtain seed yield.

One soil core at incremental depths of 0.25 m up to 0.50 m in 2003 (core diameter of 30 mm) and up to 1 m in 2004 and 2005 (core diameter of 70 mm in Saskatoon and SPG and 80 mm at Swift Current) was removed from between the two centre rows of each plot at seeding and harvest. Soil cores were dried at 105 °C until constant weight and gravimetric soil water content was then calculated as the difference between the initial and dried core weights divided by the dry weight. Bulk density of each soil core was determined as the quotient of dry weight and core volume and then volumetric water content was calculated as the product of gravimetric water content and bulk density.

Water use was calculated from the water balance equation as

$$WU = ET = \text{rainfall} + SM_{\text{seedng}} - SM_{\text{harvest}} - R - D \quad [5.3]$$

where WU and ET (evapotranspiration) are the water use via plant transpiration and direct evaporation from soil surface, R is runoff, D is deep drainage and SM_{seeding} and SM_{harvest} are the volumetric soil moisture at seeding and harvest, respectively. Runoff and deep drainage were assumed to be negligible in this experiment (Angus and van Herwaarden, 2001; Miller et al. 2001). The experimental plots were also relatively flat with a slope of $< 5^\circ$.

Other calculated variables were WUE_{biomass} as maximum biomass per WU and WUE for seed yield (WUE_{seed}) as seed yield per WU. Daily rainfall and temperature data were logged daily using automated weather stations at the Goodale and Swift Current locations (Table 5.3).

5.2.3 Statistical Analysis

All statistical analyses were performed using SAS version 9.0 (SAS Institute, 1999 Cary, NC, USA). For all variables, outliers were detected based on cultivar–target PPD combinations for Student’s Residual regressions and values greater than 2.0 or less than

Table 5.3 Seasonal rainfall (mm) measured from seeding to harvest and mean seasonal air temperature (°C) at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

Month	2003		2004	2005		Long term ^z	
	Goodale	SPG	Goodale	Goodale	Swift Current	Saskatoon	Swift Current
	<u>Rainfall (mm)</u>						
May	14	14	36	28	22	42	44
June	31	31	87	173	123	63	66
July	64	64	75	57	21	58	52
Aug	31	31	73	84	52	37	40
Sept	39	39	25	92	41	30	28
Total	133	128	273	435	254	230	230
	<u>Mean temperature (°C)</u>						
May	12	12	8	10	10	12	11
June	16	16	13	15	15	16	16
July	18	18	18	18	19	19	18
Aug	21	21	15	16	17	17	18
Sept	11	11	12	12	13	11	12
Mean	17	17	13	14	14	15	15

^z Long term (1970 – 2000) average for Saskatoon (Goodale and SPG) and Swift Current from Environment Canada (2006).

-2.0 were removed from the analyses (Appendix 3). Data were analyzed for each location-year separately because actual PPD varied over locations and years.

Analysis of variance for crop stand, WU, maximum biomass, CGR, seed yield, WUE_{biomass} , WUE_{seed} and HI were performed using the PROC MIXED procedure with replicate as random effect and cultivar and PPD as fixed effects. The default modified Tukey's statistic of the PROC MIXED procedure was used for mean separation at $P < 0.05$ and mean separation output were then converted to letter groupings (Saxton, 1998). Not all combinations of canopy traits (leaf type x growth habit) were possible, so contrast statements were used to separate means for leaf type and growth habit.

5.3 RESULTS

Results from SPG 2004 were excluded from the analyses because of extreme late seeding on June 5 which was exacerbated by an early frost on August 20 resulting in a failure of the crop to fully mature. The cultivars CDC ChiChi and Evans in replications 1 and 3 at Goodale in 2005 were also deleted from the analysis because of severe ascochyta blight infestation.

5.3.1 Weather Effects

The three years varied considerably in seasonal rainfall and mean temperature, which is not uncommon on the Canadian Prairies (Table 5.3). The first season, 2003, was a warm, dry and relatively short season whereas 2004 and 2005 had more moisture and lower temperatures than the long-term average. In 2004, an early frost on August 20 together with 0.24 m of snow in October at Goodale lead to a very late harvest on November 10 (Table 5.1).

5.3.2 Plant Population Density

The high PPD levels attained (56 to 58 plants m^{-2}) were significantly greater than the recommended PPD levels attained (33 to 42 plants m^{-2}) at all location-years (Table 5.4). Despite over-seeding by 15% for each location-year, stand counts were lower than the targeted 45 and 75 plants m^{-2} . The lowest stand counts were noted in 2003 possibly because of a dry seed bed at seeding at both Goodale and SPG locations. Table 5.5 shows the percentage of actual stand to target PPD to be higher for the lower recommended PPD (45 plants m^{-2}) than for the high PPD (75 plants m^{-2}) in all location-years except at Goodale in 2003. The much larger difference between the actual and target stand counts at the higher target PPD may be due to intra-row plant competition as row-spacing was kept constant while increasing number of plants in a row to increase the PPD.

5.3.3 Water Use

Volumetric soil water content at seeding and harvest were significantly different in all location-years at all depths except at the 1 m depth at Goodale in 2005 (Figs. 5.1, 5.2 and

Table 5.4 Target and actual plant population density of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

Target (plants m ⁻²)	Actual plant population density (plants m ⁻²)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
45	33b	38b	41b	40b	42b
75	56a	58a	56a	58a	57a

^z Means within a column followed by the same letter are not significantly different at P < 0.05 (Tukey's test).

Table 5.5 Percent of actual to target plant population density of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2004) and Swift Current (2005).

Target (plants m ⁻²)	Percent of actual to target plant population density				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
45	73	84	91	89	93
75	75	77	75	77	76

5.3). Significant differences at the lowest sampling depth of 1.0 m indicate that the chickpea crop extracted water below this depth. This is particularly so in 2003 where soils were sampled up to only the 0.5 m depth.

Gravimetric soil water content was generally significantly lower at harvest than at seeding except at Goodale in 2004 at the 0.25 and 1.0 m depth and at Goodale in 2005 at all depths (Fig. 5.1). The re-charge of the soil profile noted at Goodale in 2004 and 2005 may be due to late-season rains which are not uncommon on the Canadian Prairies. Inclement end-of-season weather was experienced in 2004 with about 24 cm of snow in October and about 46% more rainfall in August and September than the long term average. At Goodale in 2005, about 163% more rain fell in August and September than the long term average.

Overall, experimental treatments had minimal effect on volumetric soil water content at both seeding and harvest for any given soil depth (Figs 5.1, 5.2 and 5.3). For both leaf type and growth habit, minimal differences in volumetric water content noted at harvest were not consistent across both depth and location-years and PPD showed no effect whatsoever at all depths and location-years.

Seasonal WU did not show a consistent response to leaf type (Table 5.6). While no effect was seen in two location-years (SPG 2003 and Swift Current 2005), the unifoliate cultivar had significantly higher WU at Goodale in 2003 and 2005 but the situation was reversed in 2004 where WU was significantly higher for the fern cultivars. Growth habit did not show a consistent effect on WU. Similar to leaf type, no effect was seen at two location-years (SPG 2003 and Swift Current 2005). The bushy cultivars had significantly higher WU than the erect and spreading cultivars at Goodale in 2004 but at the same location in 2005, the bushy had significantly lower WU than the other two growth habits. At Goodale in 2003, WU for the bushy cultivars was intermediate between that of the erect and spreading growth habits. Plant population density showed no effect on WU in all five location-years.

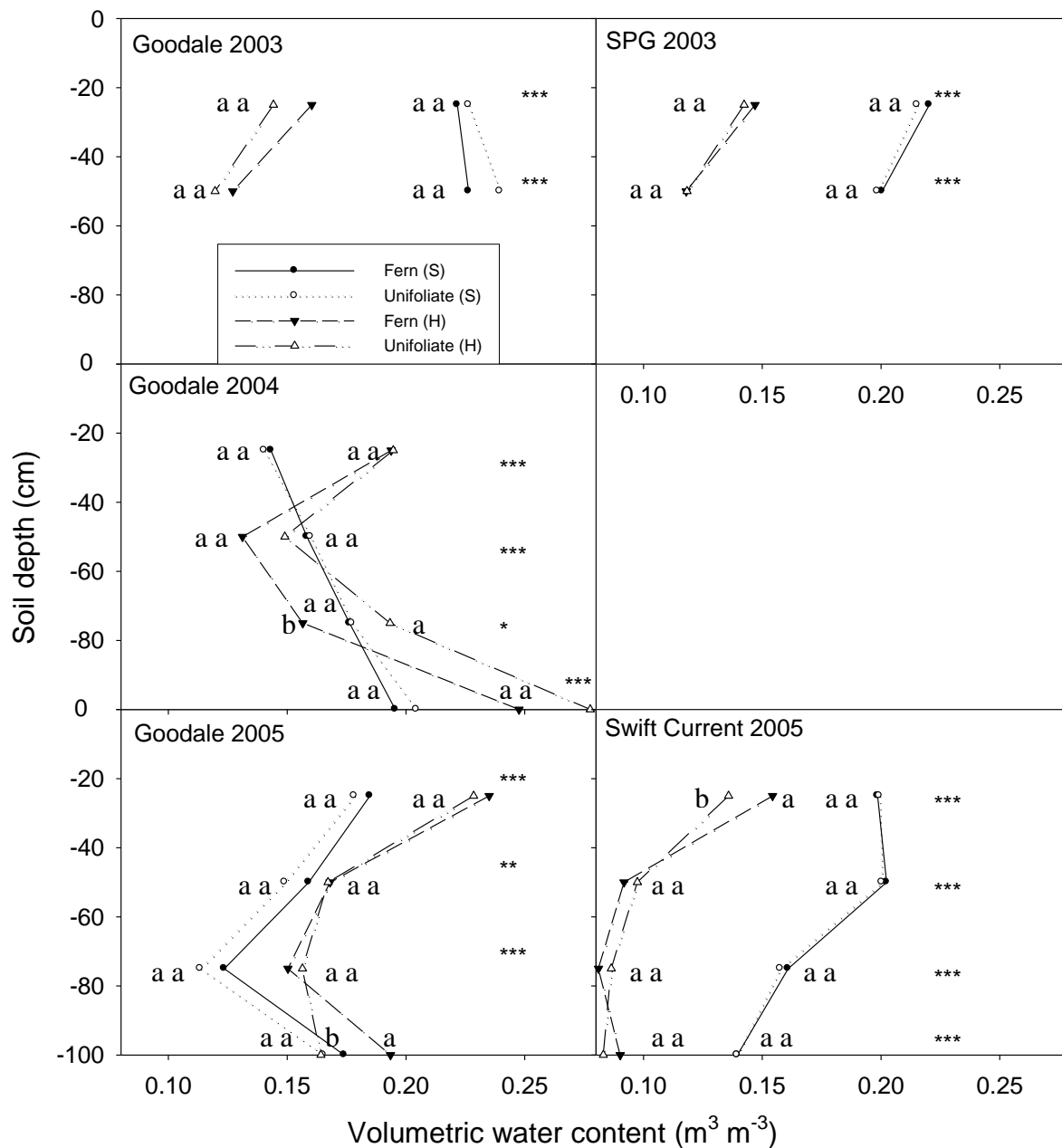


Fig. 5.1. Seeding (S) and harvest (H) volumetric soil water content of fern and unifoliolate chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replicates and two plant densities. Means of leaf types at seeding or harvest at a given depth with same letter are not significantly different at $P < 0.05$. *, ** and *** indicate significant differences between seeding and harvest treatments means for a given depth at $P < 0.05$, 0.01 and 0.001, respectively.

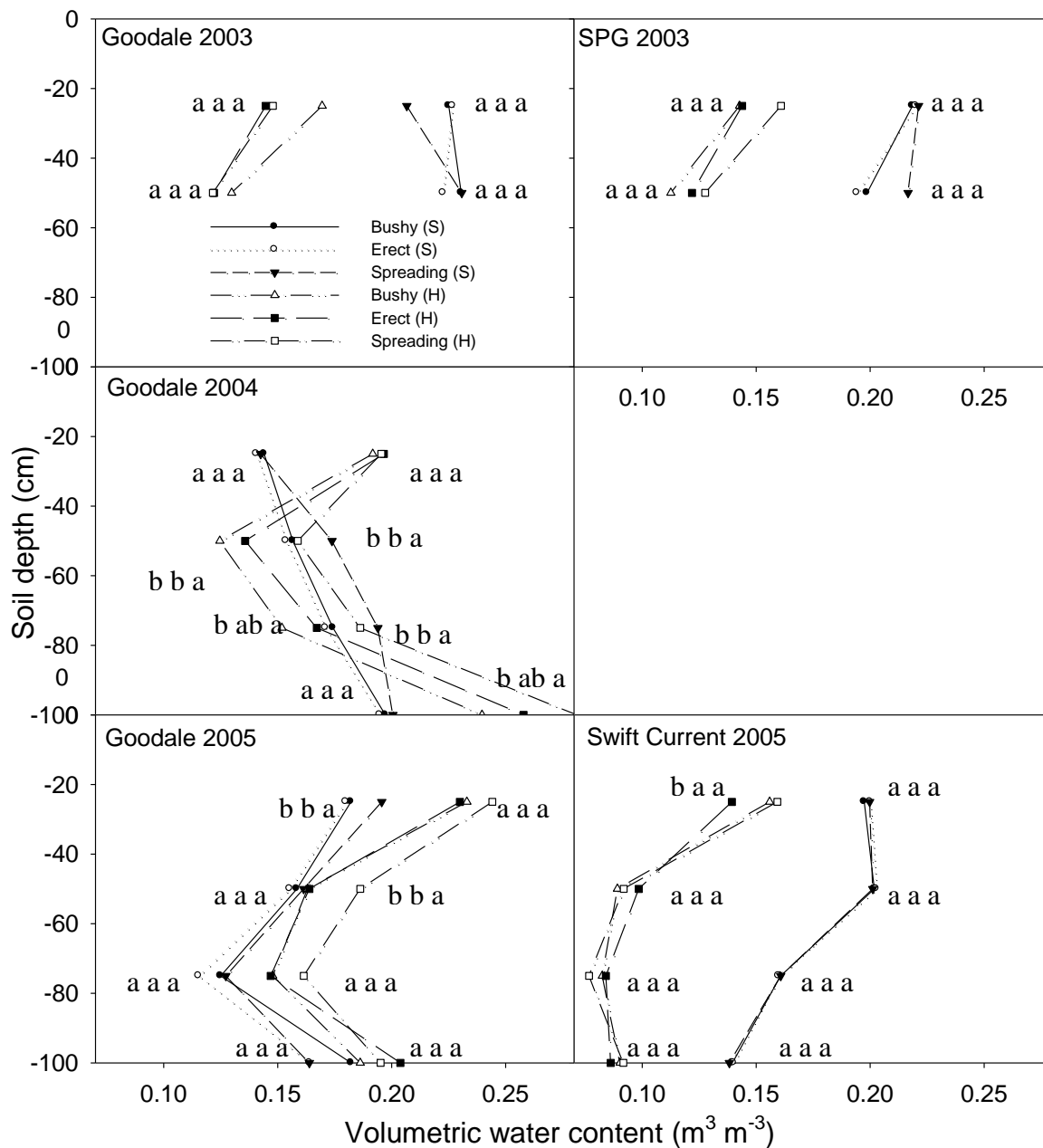


Fig. 5.2. Seeding (S) and harvest (H) volumetric soil water content of bushy, erect and spreading chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replicates and two plant densities. Means of growth habits at seeding or harvest at a given depth with same letter are not significantly different at $P < 0.05$.

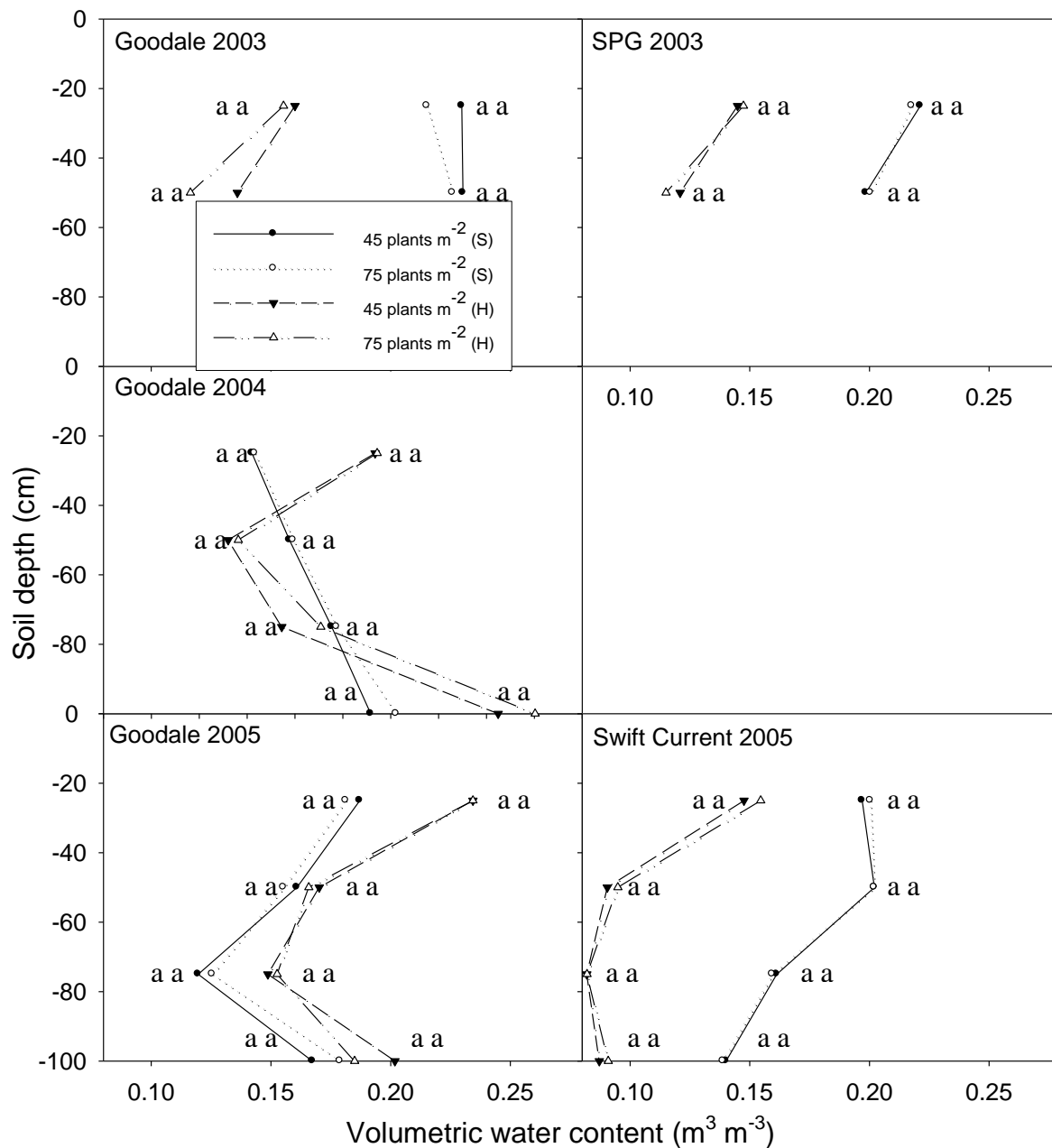


Fig. 5.3. Seeding (S) and harvest (H) volumetric soil water content of target chickpea plant density of 45 and 75 plants m⁻² at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replicates and two plant densities. Means of plant densities at seeding or harvest at a given depth with same letter are not significantly different at P < 0.05.

Table 5.6 Water use of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	Water use (mm)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
<u>Leaf type</u>					
Fern	223b	183a	230a	434b	353a
Unifoliolate	269a	178a	210b	538a	361a
<u>Growth habit</u>					
Bushy	228ab	180a	236a	411b	351a
Erect	245a	186a	223b	456a	361a
Spreading	209b	180a	209b	505a	354a
<u>Target (plants m⁻²)</u>					
45	235a	178a	235a	448a	359a
75	225a	186a	221a	446a	351a

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

5.3.4 Seasonal Biomass Accumulation and Maximum Biomass

In all location-years, biomass accumulation during the first-half of the season with the exception of Swift Current in 2005 was generally significantly higher for cultivars with unifoliolate leaves than cultivars with fern leaves (Fig. 5.4). The lack of differences at Swift Current in 2005 may be due to the fact that the first biomass sampling was late (64 DAS) compared to the other location-years. During the second-half of the season both leaf types had similar biomass or the fern cultivars accumulated significantly higher biomass.

Significant differences were noted amongst growth habits in the first-half of the season but differences were generally not significant in the second-half of the season except for the penultimate samplings at Goodale and Swift Current in 2005 (Fig. 5.5). In the first-half of the season at Goodale in 2003 and 2004 and SPG in 2003, the spreading cultivar tended to have lower biomass than the bushy and erect cultivars (Fig 5.5). However at Goodale and Swift Current in 2005, the spreading cultivar tended to accumulate higher biomass than the bushy and erect cultivars.

The higher target PPD of 75 plants m^{-2} generally accumulated greater biomass than the lower recommended target PPD of 45 plants m^{-2} throughout the season in all location-years. (Fig. 5.6). Differences between the two PPDs were generally significant up to about 70 DAS, after which the differences generally became non-significant.

Regarding maximum biomass accumulated over the season, leaf types did not affect maximum biomass in three out of five location-years but the unifoliolate cultivar had significantly higher maximum biomass at Goodale in 2003 while the fern cultivars had significantly higher maximum biomass at SPG in 2003 (Table 5.7). Growth habit and PPD showed no significant effect on the maximum biomass attained in the season in all location-years (Table 5.7). Relatively low maximum biomass values were observed at both locations in the dry year of 2003 with the overall lowest maximum biomass (349 g m^{-2}) being noted for the fern leaf type and the 45 plants m^{-2} target PPD at Goodale in

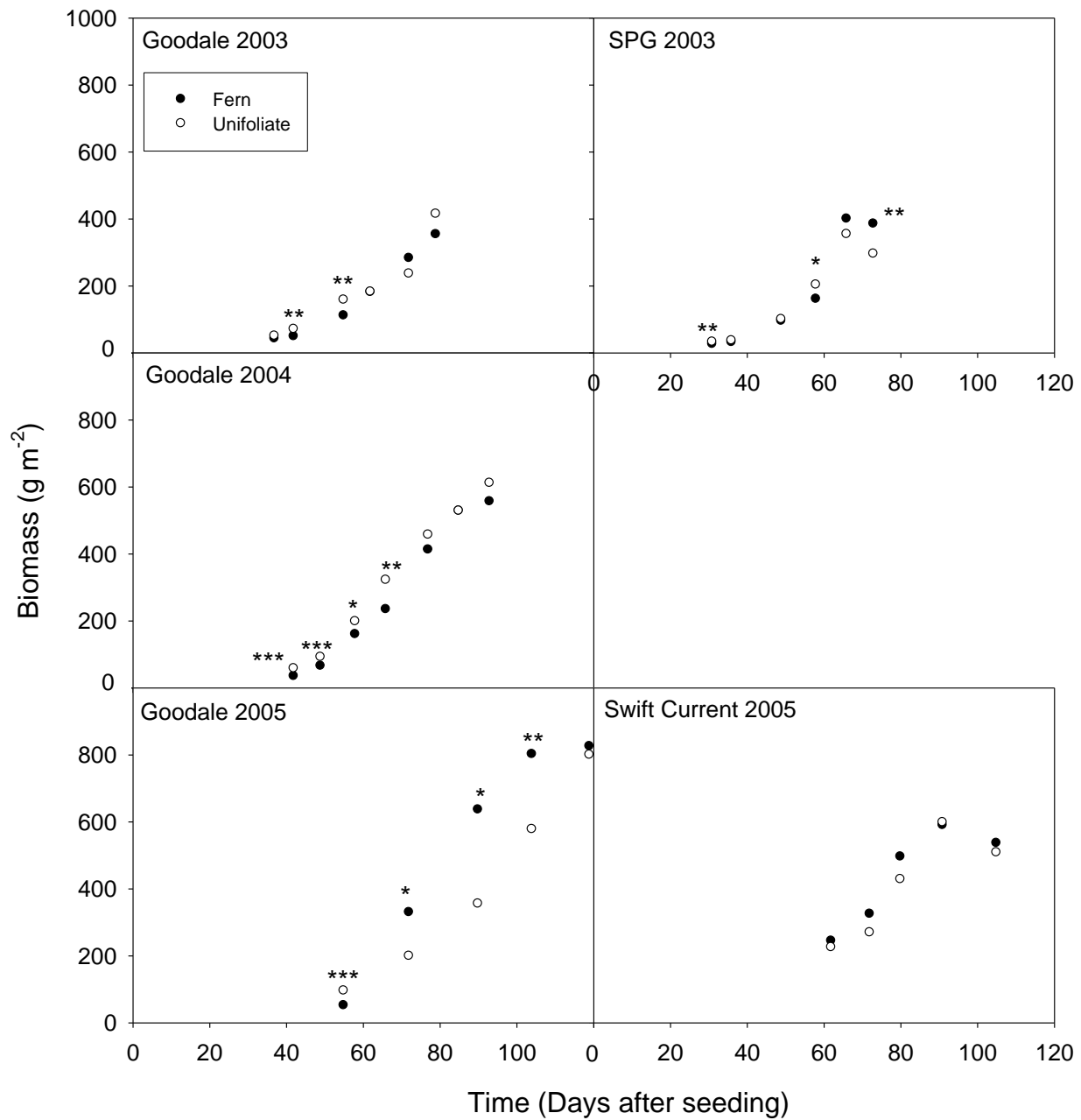


Fig. 5.4 Biomass accumulation of fern and unifoliolate leaf types in chickpea over the growing season at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replications and two plant densities. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001 , respectively.

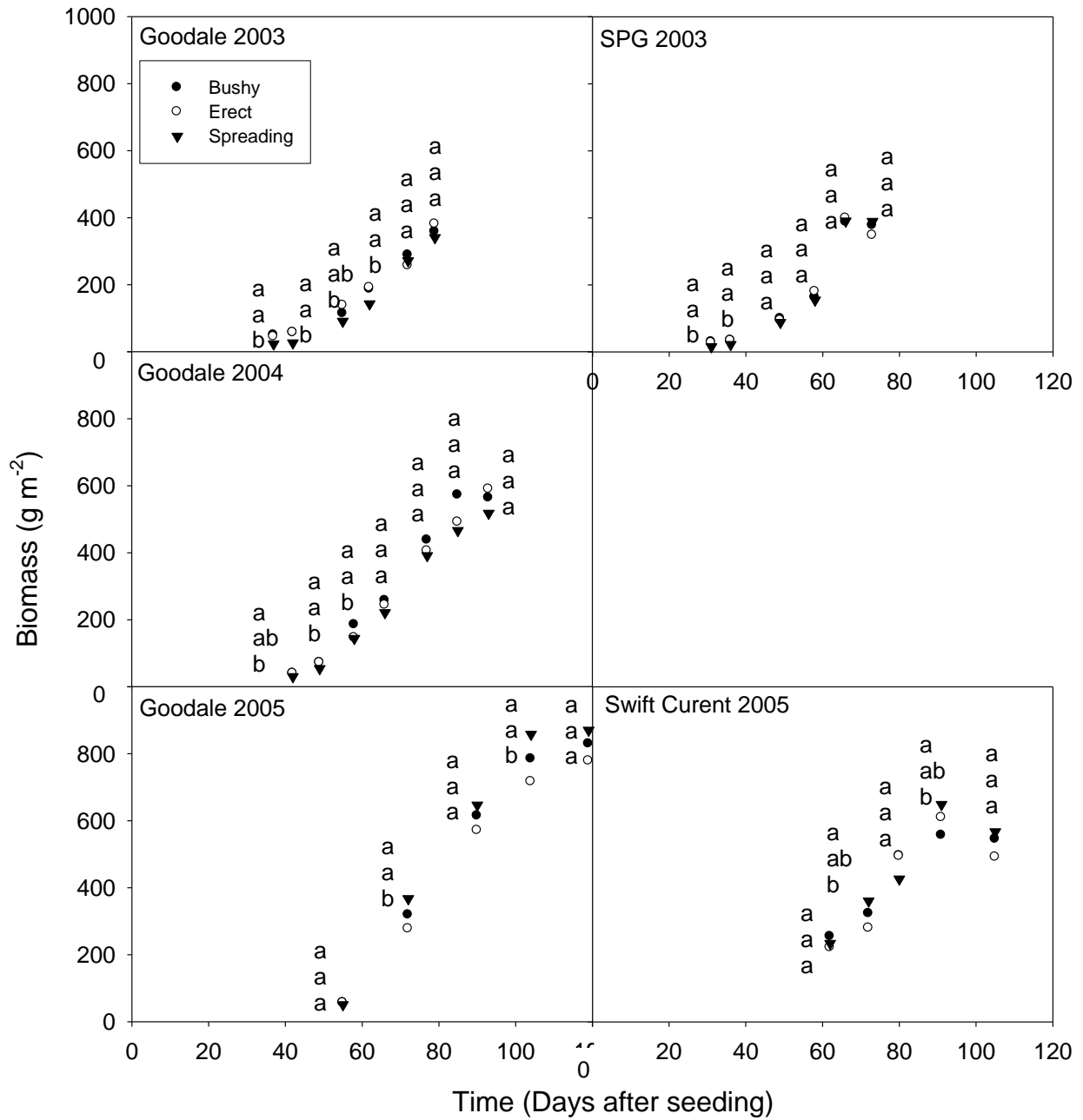


Fig. 5.5 Biomass accumulation of bushy, erect and spreading growth habits in chickpea over the growing season at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replications and two plant densities. Means with same letter are not significantly different at $P < 0.05$.

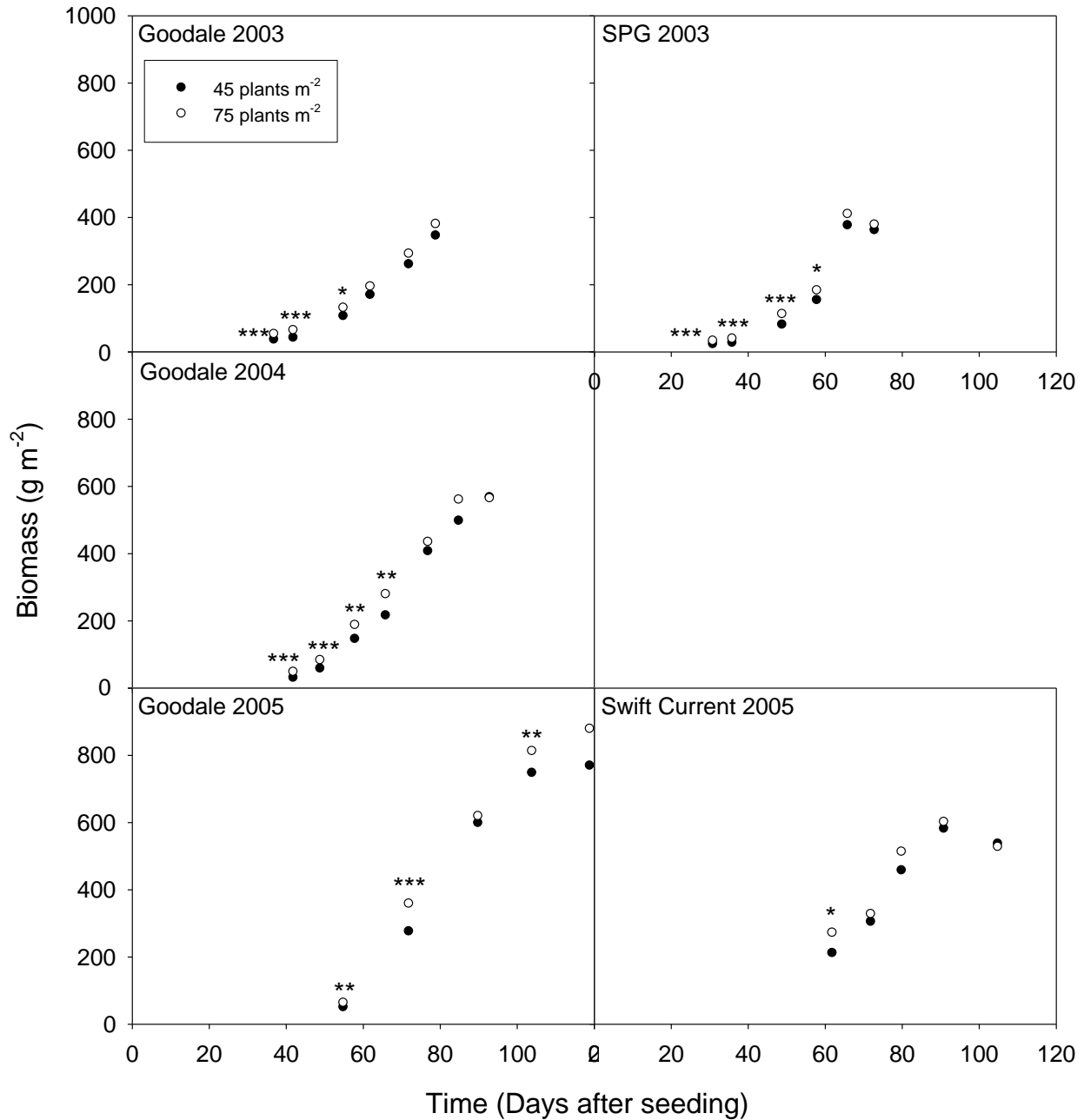


Fig. 5.6 Biomass accumulation of chickpea plant population density at 45 and 75 plants m⁻² over the growing season at Goodale (2003 to 2005), SPG 2003 and Swift Current 2005. Data points represent treatment means of four replications. *, ** and *** indicate significant difference at P < 0.05, 0.01 and 0.001, respectively.

Table 5.7 Maximum biomass of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	Maximum biomass (g m ⁻²)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
<u>Leaf type</u>					
Fern	349b	429a	623a	824a	589a
Unifoliolate	414a	367b	656a	799a	597a
<u>Growth habit</u>					
Bushy	355a	421a	662a	829a	553a
Erect	372a	409a	613a	778a	609a
Spreading	350a	430a	563a	870a	649a
<u>Target (plants m⁻²)</u>					
45	349a	402a	638a	748a	588a
75	369a	431a	624a	813a	587a

^z Treatment means within a column followed by the same letter are not significantly different at P < 0.05 (Tukey's test).

2003. The highest maximum biomass (870 g m^{-2}) was noted at Goodale in 2005 which was the location-year with the highest seasonal rainfall of 434 mm.

5.3.5 Crop Growth Rate

Treatment differences in CGR closely reflected seasonal biomass accumulation (Figs. 5.7, 5.8 and 5.9). The unifoliolate cultivars showed higher CGR early in the season, up to about 50 DAS, after which the CGR of the fern cultivars generally was higher (Fig. 5.7). The bushy and erect cultivars showed higher CGR than the spreading cultivar early in the season, up to about 50 DAS, after which differences in CGR amongst growth habits were generally not significant (Fig. 5.8). The 75 plants m^{-2} target PPD also showed significantly higher CGR than the recommended 45 plants m^{-2} PPD from early to mid-season, after which differences were not significant (Fig. 5.9).

5.3.6 Seed Yield

Cultivars with fern leaves produced significantly higher seed yields in all location-years (Table 5.8). The erect cultivars had significantly lower yields than the bushy and spreading cultivars in all location-years. The bushy and spreading cultivars did not show a distinct advantage over each other with respect to seed yield. The bushy cultivars had significantly higher seed yield than the spreading cultivar in two location-years, significantly lower seed yield in one location-year and no significant difference in two location-years. Seed yield was higher for the higher PPD in all location-years but differences were significant in only two out of five location-years. The highest seed yield (423 g m^{-2}) was achieved by the spreading cultivar at Goodale in 2005 while the lowest yield (62 g m^{-2}) was obtained for the unifoliolate cultivar at SPG in 2003. Overall, yields were lower in the dry year of 2003 than the wetter years of 2004 and 2005.

5.3.7 Water Use Efficiency

No treatment effects were noted for $\text{WUE}_{\text{biomass}}$ with the unifoliolate leaf type having both the highest and lowest values of 3.02 and $1.52 \text{ g m}^{-2} \text{ mm}^{-1}$ at Goodale in 2004 and at

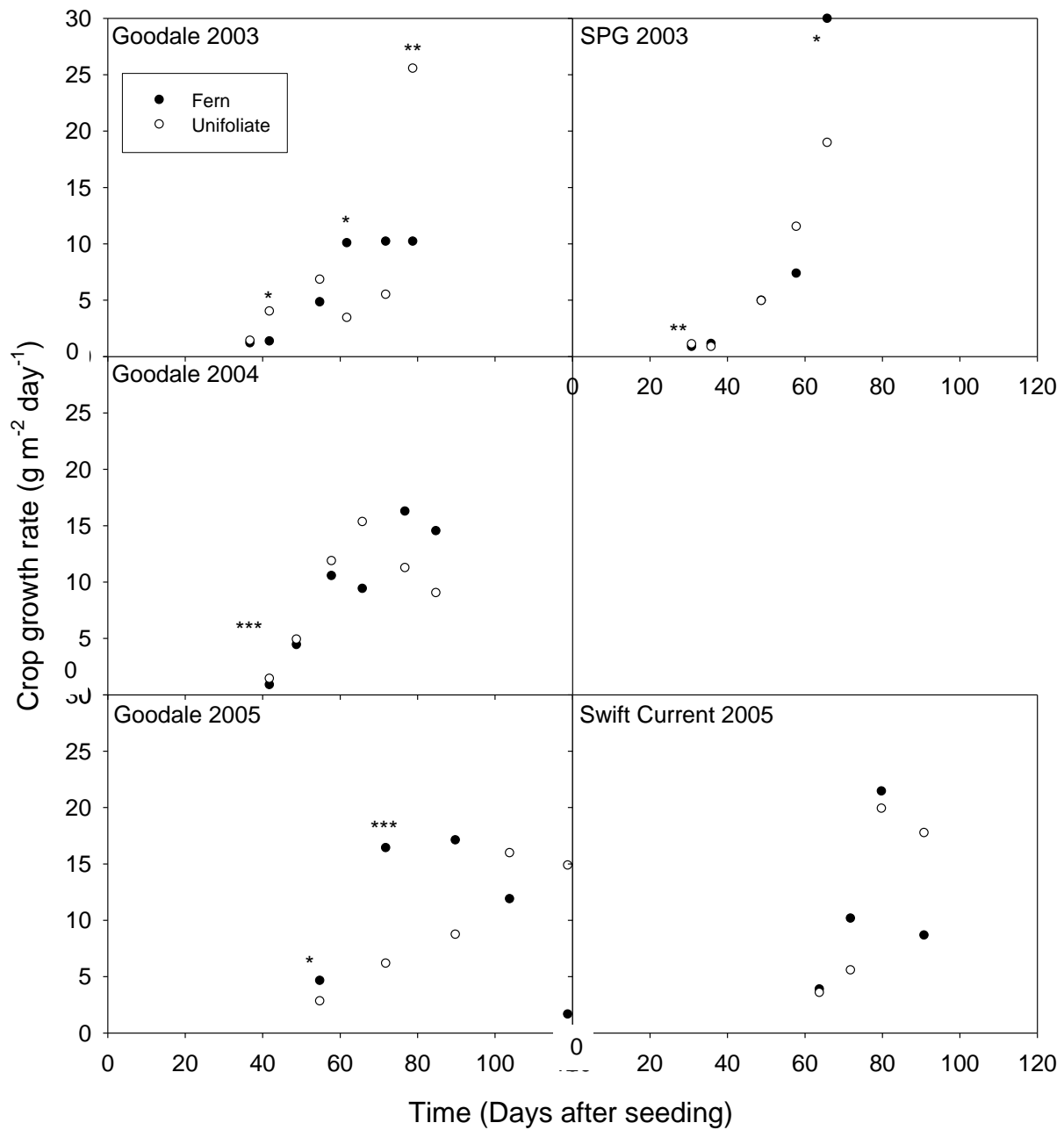


Fig. 5.7 Crop growth rate of two fern and unifoliate leaf types in chickpea over the growing season at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replications and two plant densities. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001 , respectively.

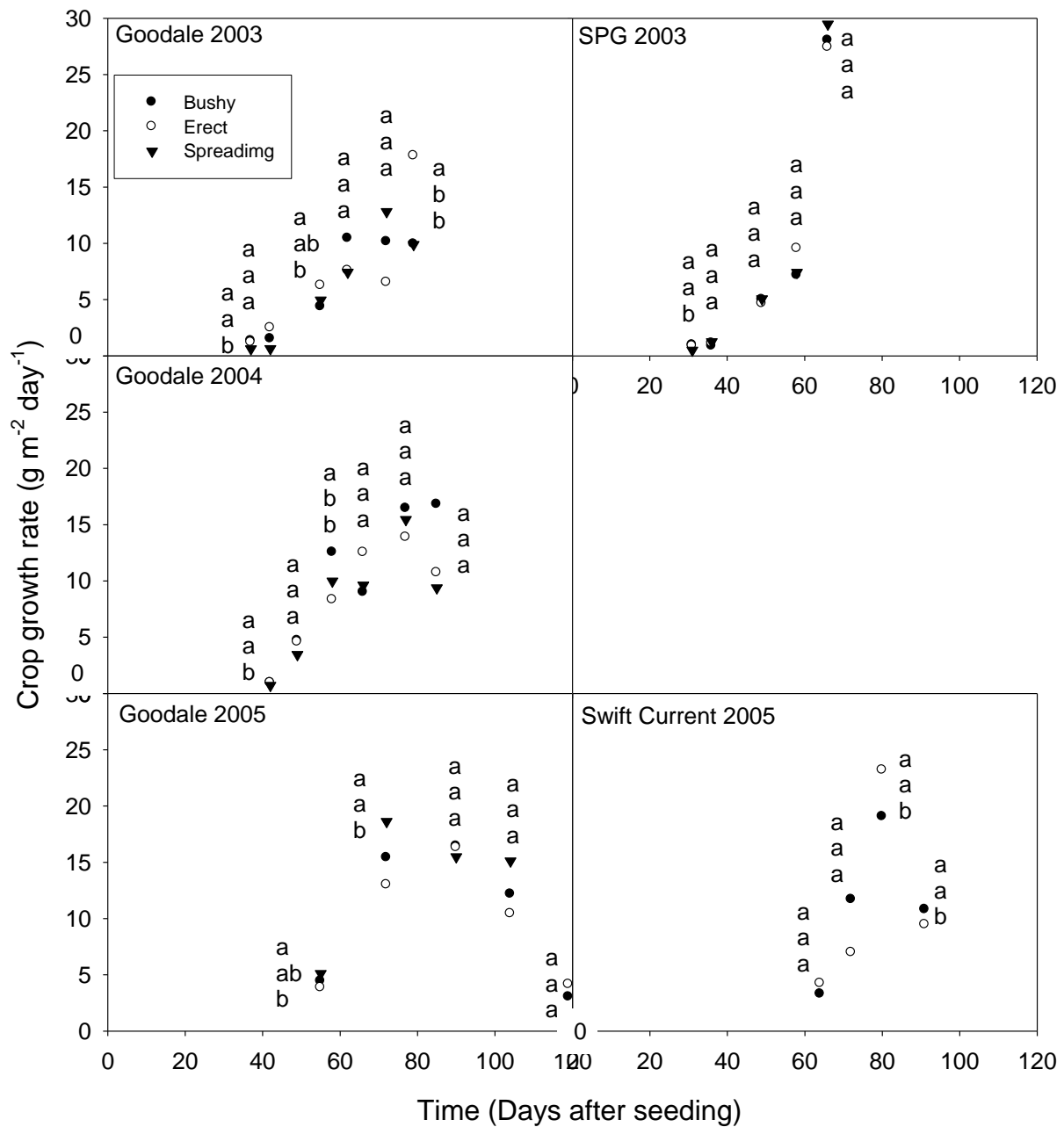


Fig. 5.8 Crop growth rate of bushy, erect and spreading growth habits in chickpea over the growing season at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replications and two plant densities. *, ** and *** indicate significant difference at $P < 0.05$, 0.01 and 0.001 , respectively.

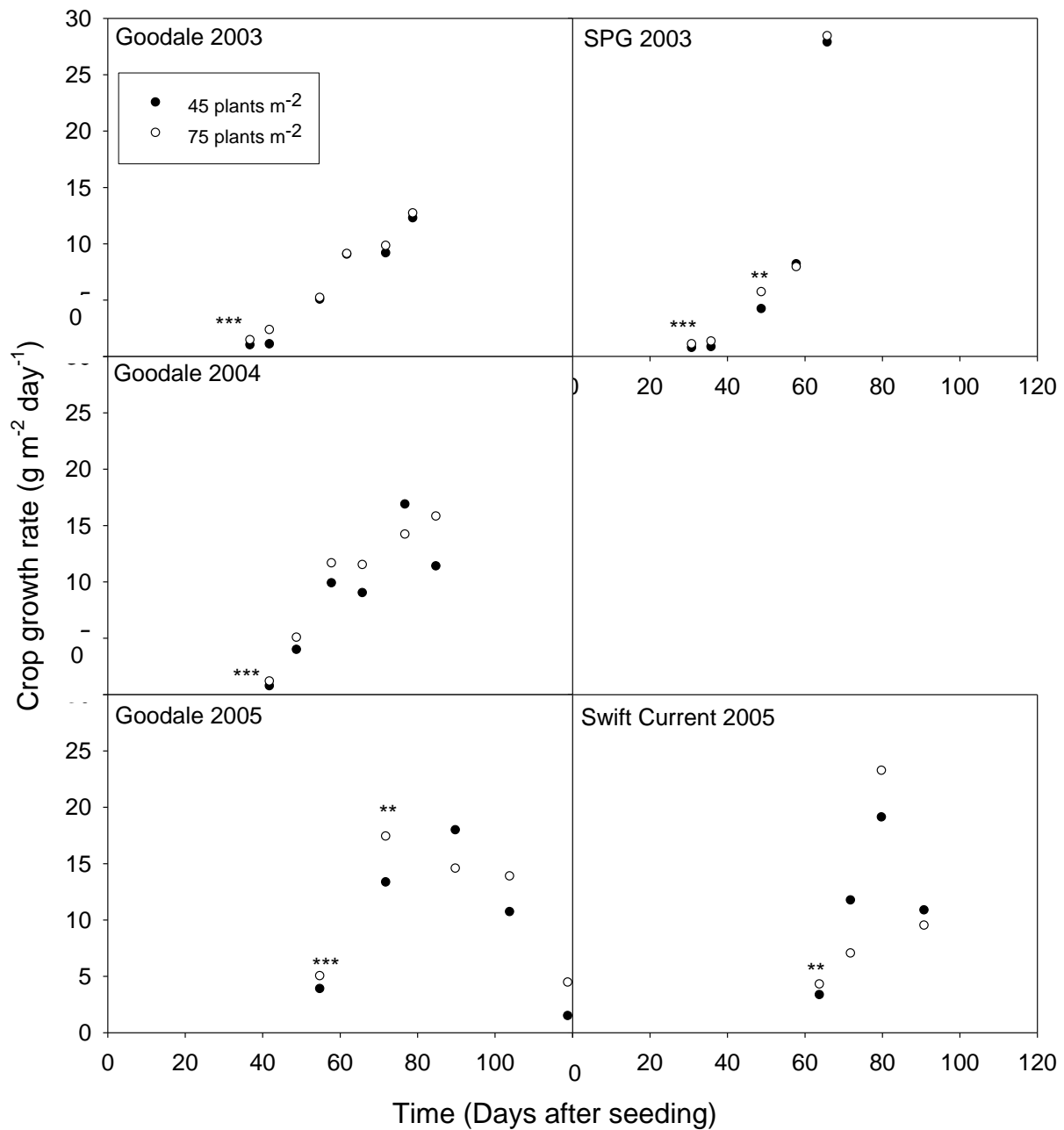


Fig. 5.9 Crop growth rate of chickpea cultivars at 45 and 75 plants m⁻² over the growing season at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005). Data points represent treatment means of four replications. *, ** and *** indicate significant difference at P < 0.05, 0.01 and 0.001, respectively.

Table 5.8 Seed yield of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	Seed yield (g m ⁻²)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
<u>Leaf type</u>					
Fern	119a	193a	222a	355a	227a
Unifoliate	90b	62b	98b	71b	122b
<u>Growth habit</u>					
Bushy	129a	193a	236a	338b	226a
Erect	90c	134b	157c	246c	172b
Spreading	113b	196a	206b	423a	235a
<u>Target (plants m⁻²)</u>					
45	110a	166a	186b	284a	201b
75	119a	174a	216a	288a	218a

^z Treatment means within a column followed by the same letter are not significantly different at P < 0.05 (Tukey's test).

Goodale in 2005, respectively (Table 5.9). However, significant differences were noted in the response of WUE_{seed} to all treatments (Table 5.10). The response of WUE_{seed} to treatments was strikingly similar to that of seed yield with the fern cultivars having significantly higher WUE_{seed} in all location-years and the erect cultivars having significantly lower WUE_{seed} than the bushy and spreading cultivars in all location-years. The higher PPD tended to have higher WUE_{seed} than the lower PPD but differences were significant in only two of the five location-years. The WUE_{seed} ranged from 0.14 for the unifoliate cultivar at Goodale in 2005 to $1.12 \text{ g m}^{-2} \text{ mm}^{-1}$ for the spreading cultivar at SPG in 2003.

5.3.8 Harvest Index

Treatment effects on HI were also quite similar to that of seed yield. Cultivars with fern leaves had significantly higher HI than the cultivar with unifoliate leaves in all location-years (Table 5.11). Regarding growth habit, the spreading and erect cultivars tended to have highest and lowest HI, respectively, with the bushy cultivars having intermediate values. Harvest index was more or less neutral in response to PPD with no significant difference in four location-years and the high PPD having significantly higher PPD in one location-year. The highest HI of 0.55 was noted for the spreading cultivar at Goodale in 2003 while the lowest of 0.19 was noted for the unifoliate cultivar at SPG in 2003.

Table 5.9 Water use efficiency for biomass of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	Water use efficiency for biomass ($\text{g m}^{-2} \text{mm}^{-1}$)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
<u>Leaf type</u>					
Fern	1.66a	2.43a	2.73a	1.90a	1.67a
Unifoliate	1.61a	1.95a	3.02a	1.52a	1.66a
<u>Growth habit</u>					
Bushy	1.63a	2.43a	2.83a	1.96a	1.60a
Erect	1.66a	2.18a	2.73a	1.74a	1.70a
Spreading	1.69a	2.44a	2.73a	1.79a	1.83a
<u>Target (plants m^{-2})</u>					
45	1.57a	2.26a	2.74a	1.62a	1.62a
75	1.72a	2.44a	2.81a	1.85a	1.71a

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

Table 5.10 Water use efficiency for seed yield of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	Water use efficiency for seed yield ($\text{g m}^{-2} \text{mm}^{-1}$)				
	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
<u>Leaf type</u>					
Fern	0.56a	1.06a	0.99a	0.80a	0.65a
Unifoliolate	0.35b	0.39b	0.49b	0.14b	0.34b
<u>Growth habit</u>					
Bushy	0.60a	1.07a	1.02a	0.80a	0.65a
Erect	0.41b	0.72b	0.71b	0.56b	0.50b
Spreading	0.50a	1.12a	1.00a	0.86a	0.66a
<u>Target (plants m^{-2})</u>					
45	0.50a	1.00a	0.81b	0.61a	0.57b
75	0.55a	0.94a	1.00a	0.68a	0.63a

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

Table 5.11 Harvest index of chickpea cultivars over five location-years at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005).

	2003		Harvest index		
	Goodale	SPG	2004 Goodale	2005 Goodale	2005 Swift Current
<u>Leaf type</u>					
Fern	0.52a	0.40a	0.41a	0.49a	0.47a
Unifoliolate	0.36b	0.19b	0.24b	0.23b	0.31b
<u>Growth habit</u>					
Bushy	0.50b	0.37b	0.39ab	0.46b	0.46a
Erect	0.44c	0.32c	0.34b	0.42c	0.40b
Spreading	0.55a	0.46a	0.42a	0.54a	0.47a
<u>Target (plants m⁻²)</u>					
45	0.47b	0.36a	0.36a	0.44a	0.44a
75	0.51a	0.38a	0.40a	0.40a	0.44a

^z Treatment means within a column followed by the same letter are not significantly different at $P < 0.05$ (Tukey's test).

5. 1 DISCUSSION

Water use efficiency has been shown to be important to crop production in drought-prone regions of the world including the semi-arid Canadian Prairies (Miller et al., 2001; Miller et al., 2002; Cutforth et al., 2002). Therefore, identifying canopy traits of chickpea cultivars that promote efficient water use will be beneficial to chickpea production on the semi-arid Canadian Prairies. In this experiment, the effects of fern and unifoliate leaf types, bushy, erect and spreading growth habits, and recommended (45 plants m⁻²) versus high PPD (75 plants m⁻²) on the parameters of the Passioura (1977) equation i.e. equation 5.1, namely seed yield, WU, WUE and HI were assessed.

Seasonal WU did not generally vary significantly amongst treatments, i.e., leaf type, growth habit and PPD in both dry and wet location-years. Treatment differences were also not evident regarding maximum biomass accumulated over the season. Consequently, there were no significant treatment differences in WUE_{biomass}. Data on chickpea WUE_{biomass} on the Canadian Prairies is generally lacking; however, in a Mediterranean type environment, Siddique and Sedgley (1985) also found no significant differences in WUE_{biomass} between debranched and whole chickpea plants but differences in WUE_{seed} were significant. The range of WUE_{biomass} from this experiment (1.52 to 3.02 g mm⁻¹) on a m⁻² basis is comparable to that reported by Siddique and Sedgley (1986), i.e., 17.7 to 35.2 kg mm⁻¹ on a ha⁻¹ basis (1.8 to 3.5 g mm⁻¹) regarding effect of seeding date on WUE_{biomass} in South-western Australia.

The lack of treatment differences regarding maximum biomass, which is the highest biomass accumulated per plot over the season, could be attributed to indeterminacy in chickpea where both vegetative and reproductive growth continues as long as there is available moisture. Significant treatment differences were, however, noted when the time-course of biomass and CGRs were considered. The unifoliate leaf cultivars, for example, had significantly higher biomass and CGR than the fern cultivars in the early stages of the growing season but by mid-season to the end of the season, differences were generally not significant or the fern cultivars had significantly higher biomass and CGR (Figs. 5.4 and 5.7). The higher target PPD of 75 plants m⁻² also had higher biomass accumulation and CGR than the lower target PPD of 45

plants m^{-2} throughout the season but differences were generally significant only up to mid-season (Figs. 5.6 and 5.9).

Seasonal WU is the sum of transpiration and soil evaporation and as indicated by equation 5.2, $\text{WUE}_{\text{biomass}}$ is improved by increasing transpiration while decreasing soil evaporation, especially in environments where crops depend on in-season precipitation like the Canadian Prairies. Although no treatment differences in WU were noted in this experiment, treatment differences in the components of WU i.e. transpiration and soil evaporation may have contributed to the higher biomass accumulation noted for the fern cultivars than for the erect cultivars in the second half of the season. Likewise, differences in transpiration and soil evaporation may have contributed to the higher biomass accumulation of the bushy and spreading cultivars than the erect cultivars in the second half of the season. In water-limited environments, grain yield is highly dependent on post-anthesis biomass accumulation (Passioura, 1977). During the second half of the season, utilization of biomass for direct grain filling in cultivars with fern leaves and also bushy and spreading growth habits instead of contributing to structural materials in cultivars with unifoliate leaves and erect growth habits may have resulted in additional differences in seed yield production and HI.

Seed yield was significantly higher in the fern cultivars than in the unifoliate cultivars and the bushy and spreading cultivars also produced significantly higher seed yield than the erect cultivars. The higher PPD produced significantly higher seed yield in two of the three wet years but no significant differences were noted for seed yield in both locations in the dry year (2003).

Cultivars that produced significantly higher seed yields i.e. fern leaf and bushy and spreading growth habits together with the higher PPD, were found in a parallel experiment (Chapter 4) to have significantly higher maximum light interception (LI) in all but one location-year (Tables 4.2 and 4.9). Also, the time course graphs of LI (Chapter 4) and biomass (Chapter 4 and 5) showed that cultivars with high LI also had high biomass accumulation at corresponding times during the course of the growing season e.g. Figs. 4.1 and 4.7, signifying that LI contributed to biomass accumulation.

Soil water evaporation has been equated to the amount of radiation energy below the crop canopy (Brun et al., 1972; Tanner and Jury, 1976; Morgan et al., 2003) while biomass has been reported to be a poor indicator of canopy size (Richards, 1991). Therefore, using LI as a surrogate for canopy cover, it could be speculated that canopy traits with higher LI and therefore greater canopy cover, offered a better shading of the soil and thus lowered soil evaporation. Jones (1989) reported lower soil evaporation under canopies of leafed and semi-leafed peas than leafless peas and also, lower transpiration rates from lower parts of the canopy. Persaud and Khosla (1999) reported no differences in WU of three PPDs of dry-land corn (*Zea mays L.*) but soil evaporation increased and crop transpiration decreased as PPD decreased.

In this experiment, WU was not partitioned into transpiration and soil evaporation but it could be argued that during the second half of the growing season, cultivars with higher LI and thus better soil shading, consequently reduced soil evaporation, thereby using a greater part of the WU for transpiration resulting in higher biomass, CGR and subsequent seed yield.

Early vigor in cereals has been related to improvements in early season WUE (Richards and Townley-Smith, 1987; Lopez-Castaneda and Richards, 1994). In this research, the cultivars that exhibited early vigor by way of significantly higher LI (Chapter 4), biomass (Chapters 4 and 5) and CGR (Chapter 5), i.e., unifoliate leaf type and erect growth habit, did not sustain a high growth rate throughout the season. High-yielding cultivars had lower early vigor and CGRs but from around mid-season onwards, biomass, CGR and LI were higher, sometimes significantly. Therefore, mid to end of season moisture use is better correlated with seed yield, likely via improved HI for the Canadian Prairies. Early vigor and CGR may be important for improving seed yield and WUE of chickpea through reduction of soil evaporation and associated increase in transpiration (Tanner and Sinclair, 1983; Richards et al., 2000; Condon et al., 2002), particularly, in water-limited short-season production systems.

The fern leaf type, bushy and spreading growth habits and the higher PPD generally had significantly higher WUE_{seed} than the unifoliate leaf type, erect growth habit and the lower PPD, respectively. The pattern of treatment responses to WUE_{seed} was a close reflection of treatment responses to seed yield since WUE_{seed} is the quotient of seed yield and WU. Miller et al. (2006)

also reported a close relationship between WUE_{seed} and seed yield in a five-year study of three legumes including chickpea in the Brown Soil zone of the Canadian Prairies. In the current experiment, cultivars with fern leaves and bushy and spreading growth habits consistently had significantly higher HI than the unifoliate leaf type and erect growth habit, respectively, but PPD generally did not affect HI. The results of this experiment are similar to those of Siddique et al. (1990) who found that in a Mediterranean-type environment, modern cultivars of wheat had improved seed yield, WUE_{seed} and HI over old cultivars. Siddique et al. (1990) attributed the differences to increased CGRs and increased LI and associated reduced soil evaporation rates in the modern wheat cultivars.

Although maximum biomass was similar amongst treatments in this experiment, cultivars with fern leaves together with cultivars with bushy and spreading growth habits partitioned more assimilate to the seeds resulting in significantly higher seed yields than the cultivars with unifoliate leaves and erect growth habit. Harvest index was therefore the crucial factor in determining seed yield which in turn led to differences in WUE_{seed} . Harvest index had the highest correlation with seed yield in the parallel experiment (Table 4.11).

Values of WUE_{seed} reported from Swift Current in this experiment i.e. 0.34 to 0.66 $g\ m^{-2}\ mm^{-1}$ closely agree with values reported for the Brown Soil zone of the Canadian Prairies by Miller et al. (2001) ranging from 2.2 to 6.1 $kg\ ha^{-1}\ mm^{-1}$ (0.2 to 0.6 $g\ m^{-2}\ mm^{-1}$) and Miller et al., (2006) ranging from 1.9 to 7.7 $kg\ ha^{-1}\ mm^{-1}$ (0.2 to 0.8 $g\ m^{-2}\ mm^{-1}$). At Goodale and SPG, WUE_{seed} values obtained in this experiment, i.e., 0.35 to 1.12 $g\ m^{-2}\ mm^{-1}$ fell within the range specified by Miller et al. (2002) for the northern Great Plains, i.e., 2.5 to 13.6 $kg\ ha^{-1}\ mm^{-1}$ (0.3 to 1.4 $g\ m^{-2}\ mm^{-1}$).

The higher PPD in this experiment did not negatively affect WU, biomass, CGR, seed yield, $WUE_{biomass}$, WUE_{seed} and HI through competition, possibly by offering better shading of soil to reduce soil evaporation. Under Saskatchewan conditions, increased seed yield resulted in increased WUE_{seed} of no-tillage winter wheat in response to increased seeding rate and decreased row-spacing (Tompkins et al., 1991). Increasing PPD from the currently recommended 45 plants m^{-2} to 57 plants m^{-2} (average stand count of the higher targeted PPD over five location-years),

therefore, has the potential to significantly increase chickpea seed yields, especially in wet years. The advantages of a higher seed yield, WUE_{seed} and HI of the fern-leaved cultivars as well as the cultivars with bushy and spreading growth habits were evident in all location-years i.e. under both dry and wet conditions. Fern leaves together with bushy and spreading growth habits and higher PPD would therefore be valuable to breeding programs seeking to increase and stabilise chickpea seed yield for the short-season Canadian prairie environment.

6.0 GENERAL DISCUSSION AND CONCLUSIONS

Chickpea has a fairly short history on the Canadian Prairies, therefore, the urgent need for ongoing research to identify both management practices and morpho-physiological traits that adapt chickpea to this environment to improve yield. Crop yield is highly dependent on the interaction of genetic and environmental factors and so no one chickpea ideotype will be suitable for the varied environments around the world where the crop is grown. The focus of this study was to determine the PPD that produces the maximum seed yield as well as canopy architecture traits that maximize the limited resources of the short-season Canadian prairie environment to produce high and stable seed yields.

6.1 Optimizing Chickpea Population Density for the Canadian Prairies

Current recommended chickpea PPD for the Canadian Prairies is 44 plants m^{-2} based on preliminary studies (Saskatchewan Pulse Growers, 2002) and a subset of four cultivars at a narrow agronomic range of 20 to 50 plants m^{-2} (Gan et al., 2003a). New chickpea cultivars with varying canopy architecture traits have since been developed by the CDC breeding program of the University of Saskatchewan for producers in the Northern Great Plains, therefore, re-evaluating the PPD that produces the maximum seed yield for varying chickpea cultivars was highly warranted.

The results of this research showed that when maximum yield PPD, i.e., the PPD at which the highest seed yield was obtained, is averaged over the experimental years for each location (soil zone) for each treatment, a PPD of at least 55 plants m^{-2} produced a 23% to 49% seed yield above that of the current recommended PPD of 44 plants m^{-2} . In two instances where the average maximum yield PPD was less than 55 plants m^{-2} , i.e. 49 and 54 plants m^{-2} , seed yield advantages were 0 and 9%, respectively, both in the Dark Brown Soil zone. Otherwise, maximum yield PPD ranging from 56 to 61 plants m^{-2} in the Dark Brown Soil zone increased seed yield by 23 to 29%, respectively, above the currently recommended PPD. The results of this study therefore support the high-yield-system-in-place (HYSIP) concept proposed for soybean production systems in Ohio, United States (Cooper, 1989) which suggests that taking advantage of a higher seed yield

average over the long term as compared to periodic low seed yield episodes will be more profitable to producers.

Increasing PPD also increased lowest pod height significantly in all but one location-year similar to the findings of Jettner et al. (1999) and Gan et al. (2003a). Increasing optimum PPD also has the added advantage of enhanced weed control (Anderson 2005). Increasing optimum PPD of chickpea, therefore, has the potential to lower production cost to farmers by reducing damage to combines as well as cost of herbicide applications.

In addition, the results of this study did not show an explicit increase in disease severity or decrease in individual seed size with increase in PPD. No significant effect of increasing PPD on ascochyta blight severity was noted at five out of eight growth stage-years but significant increases were noted at the remaining three growth stage-years. Increasing PPD also increased individual seed weight in three location-years but the reverse trend was observed in one location-year. Chickpea individual seed weight in response to increasing PPD is generally neutral (Siddique et al., 1984; Gan et al., 2003a; Gan et al., 2003b; Gan et al., 2003d). The results of this research therefore suggest that increasing optimum PPD from the currently recommended PPD of 44 plants m⁻² to 55 plants m⁻² PPD would neither negatively impact individual seed size nor ascochyta blight severity, especially, when combined with good agronomic practices (Saskatchewan Pulse Growers. 2000; Saskatchewan Seed Guide, 2006).

Another advantage of a higher optimum PPD is early maturity which is highly desired trait on the Canadian Prairies. Terminal drought conditions favors maturity of the chickpea crop but on the Canadian Prairies, chickpea matures at a time of decreasing temperatures in contrast to other chickpea production regions where chickpea matures under increasing temperatures. Gan et al. (2003a) reported a 2.1 to 3.0 days advance in chickpea maturity with increasing PPD on the Canadian Prairies, possibly through greater moisture demand by the greater crop stand, thus enforcing a terminal drought.

6.2 Canopy Architecture Effects on Maximum Yield Population Density

Cultivars with unifoliate leaves generally required a higher PPD to produce maximum seed yield than cultivars with fern leaves and the average maximum yield PPD was 16% higher for the unifoliate cultivars over the fern cultivars. A higher maximum yield PPD for unifoliate cultivars than fern cultivars may be due to the fact that unifoliate leaves have a smaller surface area than fern leaves (Bueckert and Hovland, University of Saskatchewan, Canada, unpublished data; Bonfil, Goren, Mufradi, Lichtenzveig and Abbo, Agricultural Research Organization, Gilat Research Center, Israel, unpublished data in Bonfil et al., 2007) and therefore at a given PPD, the unifoliate canopy may be more open than the fern canopy. Cultivars with fern leaves showed a more closed canopy than the unifoliate cultivars by having a significantly higher percentage maximum LI at all location-years. A higher optimum PPD may therefore be required for unifoliate cultivars to achieve adequate canopy closure in order to intercept sufficient light for maximum biomass accumulation and seed yield.

No consistent pattern was observed in the response of optimum PPD to growth habit, although bushy and spreading cultivars generally had more closed canopies than the erect canopy as shown by significantly higher maximum LI at three and two out of five location-years, respectively. Differences in maximum yield PPD in semi-viney and viney genotypes in beans (*Phaseolus vulgaris* L.) were attributed to differences in determinancy (Nienhuis and Singh, 1985). Assessing chickpea growth habits with similar degrees of indeterminacy may be required to reveal differences in maximum yield PPD for varying chickpea growth habits.

6.3. Crop Stand

Percentage of actual to target stand counts decreased with increasing PPD in 11 out of 12 location-years which may be due to stiffer intra-row competition at higher PPDs as row-spacing was kept constant while increasing number of plants in a row to increase PPD. Other studies on the Canadian Prairies have reported a generally low plant stand e.g. chickpea by Miller et al. (2001), Gan et al. (2003) and Li et al. (2006) and lentil by Hanlan et al. (2006). Reasons attributed to low stand counts include mechanical damage to seed during transportation and seeding, dry seed bed and more competition at higher PPDs. Additional factors that may have contributed to the low stand counts in this study were low total rainfall and low mean

temperatures at seeding as well as possible mechanical damage to seeds during pre-seeding treatment which involved vigorous shaking of seeds and fungicidal mixture to ensure adequate coating of seeds. However, high percentage chickpea crop establishment has also been reported on the Canadian Prairies (Gan et al., 2003c; Gan et al., 2003d) and elsewhere (Beech and Leach, 1988; Leach and Beech, 1989). The causes of the low emergence rates in chickpea therefore warrant urgent study if a higher PPD is to be achieved to maximize seed yield.

6.4 Canopy Architecture Effects on Light Interception, Biomass and Harvest Index

A major limitation of chickpea production on the Canadian Prairies is the shortness of the growing season (May to August). Management practices as well as chickpea canopy traits that maximize the interception of the limited solar radiation may be valuable in improving and stabilizing chickpea seed yield on the Canadian Prairies. Light interception, RI, biomass, RUE, seed yield and HI were assessed for varying chickpea canopy types under the short season conditions of the Canadian Prairies. The aim of this experiment was to identify canopy traits that best utilize the limited resources in this environment to maximize seed yield.

6.4.1 Leaf Type Effects on Light Interception, Biomass and Harvest Index

Cultivars with fern leaves were superior to the unifoliolate cultivars with respect to maximum LI, seed yield and HI in all location-years. The fern cultivars also tended to show significantly higher maximum RI and maximum biomass but no consistent response of RUE to leaf type was noted. Better light penetration into the fern canopy due to the erectophile orientation and pinnate leaf structure may allow photosynthesis at all levels within the canopy, especially lower leaves at full canopy. This may contribute to higher HI and seed yield in the fern canopy, as compared to the planophile and semi-dissected leaves of the unifoliolate cultivars where shading of lower leaves may limit photosynthesis.

The amount of intercepted light affects the rate of leaf photosynthesis (Ludlow and Wilson, 1971; Prioul and Bourdu, 1973) and PAR attenuates with depth within a canopy (Szeicz et al. 1964, Allen and Brown, 1965 and Anderson, 1969). Beuerlein et al. (1971) reported seed yield increases in debranched soybean (*Glycine max* (L.) Merr.) plants at high PPD due to greater light penetration at flowering which resulted in higher HI and leaf efficiency i.e. seed yield per unit

leaf area. Reta-Sánchez and Fowler (2002) demonstrated that modifying leaf shape to increase light penetration into cotton (*Gossypium hirsutum* L.) canopy increased seed yield by 34%.

6.4.2 Growth Habit Effects on Light Interception, Biomass and Harvest Index

Cultivars with the bushy growth habit consistently performed better than the erect cultivars for seed yield and HI in all location-years. The bushy cultivars also showed significantly higher maximum LI and maximum RI than the erect cultivars in Swift Current but differences were not significant in Saskatoon. While no obvious advantage of early canopy closure was exhibited by any of the growth habits, probably due to the row spacing being too wide for the short growing season, the bushy cultivars tended to have greater canopy coverage in terms of greater LI and biomass accumulation over the growing season which may have contributed to higher seed yield and HI.

This higher productivity of the bushy over erect cultivars agrees with Rubio et al. (2004) who reported higher seed yield of chickpea lines with bushy growth habit than erect habit lines, and attributed it to more primary and secondary branching resulting in a higher number of reproductive nodes in the bushy habit lines. Walton (1991) reported a significant positive correlation between number of reproductive nodes and seed yield in field pea (*Pisum sativum* L.) in the dry, short-season Mediterranean type climate of Western Australia. A debranched chickpea crop derived from removal of branches produced higher seed yield through an increase in apical branches, which bore a higher number of reproductive nodes, as compared with the freely branching control (Siddique and Sedgley, 1985).

The overall performance of the spreading cultivar was intermediate between the bushy and erect cultivars regarding maximum LI, seed yield and HI. The spreading cultivar had similar maximum node number on main stem to the bushy and erect cultivars, so the average performance of the spreading cultivar could be explained on the basis of its shorter stature and possible fewer secondary and tertiary branching resulting in fewer reproductive nodes, lower seed yields and lower HI as compared with the taller bushy cultivars.

Response of RUE to growth habit was generally flat. Within species, RUE is a fairly conservative value, but reduction in RUE due to moisture stress is well documented (Hughes et al, 1987; Thomson and Siddique, 1997; Sinclair and Muchow, 1999; Tesfaye et al. 2006). The lack of differences with respect to growth habit is therefore not surprising and the lowest RUE values were noted in the drought year. The results of this study partly agree with Hughes et al. (1987) who also reported similar RI for the erect and prostrate growth habits but the erect growth habit had higher RUE than the prostrate types. However, Hughes et al. (1987) seeded most erect lines at higher PPD of 60 plants m⁻² while all the prostrate lines were seeded at 30 plants m⁻², therefore growth habit was confounded with PPD.

6.4.3 Plant Population Density Effects on Light Interception, Biomass and Harvest Index

Maximum LI and maximum biomass tended to remain fairly constant with increasing PPD but the time-course graphs of LI and biomass accumulation as well as that of maximum seasonal RI showed a general increasing trend in response to increasing PPD on each sampling date. Maximum RI also showed an increasing trend with increasing PPD. High PPD canopies therefore captured more light over the growing season, resulting in an increase in biomass accumulation and higher seed yield. Generally, HI remained constant with increasing PPD across location-years, although RUE generally decreased as PPD increased, but seed yield generally increased with increasing PPD.

Hughes et al. (1987) also found a chickpea canopy of 60 plants m⁻² to have a higher RI but utilize it less efficiently for total biomass accumulation i.e. RUE, than the 30 plants m⁻² canopy. A stable HI with increasing PPD (Ball et al., 2000) but decreasing RUE with increasing PPD in short-season soybean (Purcell et al., 2002) have also been reported. Purcell et al. (2002) speculated higher lower-leaf senescence due to greater light attenuation at higher PPD and water and nutrient stress may be the cause of decreasing RUE at higher PPDs. Also, at high PPDs, proportionately less intercepted radiation goes into total biomass accumulation to maintain the proportions of starch, proteins and oils in soybean. Another factor that may play a role is the fact that more light is intercepted by the dense canopy of high PPDs but it is normally associated with greater mutual shading of lower leaves depending on canopy architecture factors such as leaf number, area, shape and orientation and steadily increasing fruit load as the season progresses.

Less intercepted light is thus available for new biomass production in addition to both the maintenance of a larger canopy and the diversion of assimilate to seed in an indeterminate crop.

6.4.4 Seed Yield Associations

A significant and positive correlation between seed yield and maximum LI, RI, maximum biomass and HI in chickpea for temperate short-season production systems was detected in this research. This is supported by a number of studies on chickpea, e.g., correlation between both HI and biomass with seed yield have been reported by Saxena et al. (1990), Silim and Saxena (1993), Rao (1996), Ayaz et al. (2004b) and Toker and Cagirgan (2004). In this current research, HI showed the strongest correlation with seed yield. Increases in yield of grain crops are commonly attributed, in part, to improved HI. In chickpea, HI values reported in recent studies show a wide range e.g. 0.30 to 0.63 (Ayaz et al., 2004b), 0.15 to 0.51 (Li et al., 2006) and 0.17 to 0.36 (Tesfaye et al., 2006). Harvest index ranged from 0.19 to 0.55 in this research and the lowest HI values were noted in 2002 which was the year with the greatest end-of-season precipitation. The low HI values were therefore, a result of heightened indeterminacy. Seed yield in chickpea could be improved by increasing and stabilizing HI possibly through early maturity, which would reduce the effect of indeterminacy caused by late rains.

Overall, the variables that were significantly and positively correlated with seed yield i.e. LI, RI, biomass and HI were also seen to be generally significantly higher for the cultivars with fern leaves and bushy growth habit. Light interception, RI and biomass also generally increased as PPD increased. Harvest index however, remained fairly constant as PPD increased, indicating that increasing PPD would not be detrimental to the harvested seed yield.

6.5 Canopy Architecture Effects on Water Use Efficiency in Chickpea

Low and variable precipitation are the main limitations of crop production on the Canadian Prairies (Cutforth et al., 1999). Water use efficiency is important to crop production in drought-prone regions of the world including the semi-arid Canadian Prairies (Miller et al., 2001; Miller et al., 2002; Cutforth et al., 2002). Therefore, identifying canopy traits of chickpea cultivars that promote efficient water use will be beneficial to chickpea production on semi-arid Canadian Prairies. In this experiment, the effects of fern and unifoliate leaf types, bushy, erect and

spreading growth habits, and recommended (45 plants m⁻²) and high PPDs (75 plants m⁻²) on seed yield, WU, WUE and HI were assessed.

Similar to the findings of the parallel experiment (Chapter 4), seed yield was significantly higher in the fern cultivars than in the unifoliolate cultivars and the bushy and spreading cultivars also produced significantly greater seed yield than the erect cultivars. The higher PPD produced significantly greater seed yield in two of the three wet years but no significant differences were noted for seed yield in both locations in the dry year (2003).

The fern leaf type, bushy and spreading growth habits and the higher PPD generally had significantly higher WUE_{seed} than the unifoliolate leaf type, erect growth habit and the lower PPD, respectively. The pattern of treatment responses to WUE_{seed} was a close reflection of treatment responses to seed yield, similar to Miller et al. (2006), since WUE_{seed} is the quotient of seed yield and WU. In this research, cultivars with fern leaves and bushy and spreading growth habits consistently had significantly higher HI than the unifoliolate leaf type and erect growth habit, respectively, but PPD generally did not affect HI. The results of this research are similar to those of Siddique et al., (1990) who found that in a Mediterranean-type environment modern cultivars of wheat had improved seed yield, WUE_{seed} and HI over old cultivars. Siddique et al. (1990) attributed the differences to increased CGRs and increased LI and associated reduced soil evaporation rates in the modern wheat cultivars.

Cultivars that produced significantly higher seed yields i.e. fern leaf and bushy and spreading growth habits together with the higher PPD, were found in the parallel experiment (Chapter 4) to have significantly higher maximum LI in all location-years. Also, the time course graphs of LI (Chapter 4) and biomass (Chapter 4 and 5) showed that cultivars with high LI also had high biomass accumulation at corresponding times during the course of the growing season signifying that LI contributed to biomass accumulation.

Maximum biomass, however, generally did not vary significantly amongst treatments, therefore, there were no significant treatment differences in WUE_{biomass}. The lack of treatment differences regarding maximum biomass could be attributed to indeterminacy in chickpea. Significant

treatment differences were, however, noted when the time-course of biomass and CGRs were considered. The unifoliolate leaf cultivars, for example, had significantly higher biomass and CGR than the fern cultivars at the early stages of the growing season but by mid-season to the end of the season, differences were generally not significant or the fern cultivars had significantly higher biomass and CGR. The higher target PPD of 75 plants m^{-2} also had higher biomass accumulation and CGR than the lower target PPD of 45 plants m^{-2} throughout the season but differences were generally significant only up to mid-season.

Seasonal WU generally did not vary significantly amongst treatments. Seasonal WU is the sum of transpiration and soil evaporation and as indicated by equation 5.2, $\text{WUE}_{\text{biomass}}$ is improved by increasing transpiration while decreasing soil evaporation, especially in environments where crops depend on in-season precipitation like the Canadian Prairies. Although no treatment differences in WU were noted in this experiment, treatment differences in the components of WU i.e. transpiration and soil evaporation, may have contributed to the higher biomass accumulation noted for the fern cultivars than for the erect cultivars in the latter half of the season. Likewise, differences in transpiration and soil evaporation may have contributed to the higher biomass accumulation of the bushy and spreading cultivars than the erect cultivars later in the season. In water-limited environments, grain yield is highly dependent on post-anthesis biomass accumulation (Passioura, 1977). During the second half of the season, utilization of biomass i.e. assimilate, for direct grain filling in cultivars with fern leaves and also bushy and spreading growth habits instead of contributing to structural materials in cultivars with unifoliolate leaves and erect growth habits may have resulted in additional differences in seed yield and HI.

Soil water evaporation has been equated to the amount of radiation energy below the crop canopy (Brun et al., 1972; Tanner and Jury, 1976; Morgan et al., 2003) while biomass has been reported to be a poor indicator of canopy size (Richards, 1991). Therefore, using LI as a surrogate for canopy cover, it could be speculated that canopy traits with higher LI and therefore greater canopy cover, offered a better shading of the soil and thus lowered soil evaporation. Jones (1989) reported lower soil evaporation under canopies of leafed and semi-leafed peas than leafless peas and also, lower transpiration rates from lower parts of the canopy. Persaud and

Khosla (1999) reported no differences in WU of three PPDs of dry-land corn (*Zea mays L.*) but soil evaporation increased and crop transpiration decreased as PPD decreased.

In this research, WU was not partitioned into transpiration and soil evaporation but it could be argued that during the second half of the growing season, cultivars with higher LI and thus better soil shading, consequently reduced soil evaporation thereby using a greater part of the WU for transpiration resulting in higher biomass, CGR and subsequent seed yield.

Although maximum biomass was similar amongst treatments in this experiment, cultivars with fern leaves together with cultivars with bushy and spreading growth habits partitioned more assimilate to the seeds resulting in significantly higher seed yields than the cultivars with unifoliate leaves and erect growth habit. Harvest index was therefore the crucial factor in determining seed yield which in turn led to differences in WUE_{seed} . Harvest index had the highest correlation with seed yield in the parallel experiment (Chapter 4).

The higher PPD in this experiment did not negatively affect WU, biomass, CGR, seed yield, $WUE_{biomass}$, WUE_{seed} and HI through inter-plant competition, possibly by offering better shading of soil to reduce soil evaporation. The advantages of a higher seed yield, WUE_{seed} and HI of the fern-leafed cultivars as well as the cultivars with bushy and spreading growth habits were evident in all location-years i.e. under both dry and wet conditions. Fern leaves together with bushy and spreading growth habits would therefore be valuable to breeding programs to increase and stabilise chickpea seed yield for the short-season Canadian prairie environment.

6.6 Early vigor

Early vigor in cereals has been related to improvements in early season WUE (Richards and Townley-Smith, 1987; Lopez-Castaneda and Richards, 1994). From two parallel experiments (Chapters 4 and 5), the cultivars that exhibited early vigor by way of significantly higher LI, biomass and CGR. Unifoliate leaf type and erect growth habit did not sustain a high growth rate throughout the season. High-yielding cultivars had lower early vigor but from around mid-season onwards, biomass, CGR and LI were higher, sometimes significantly. Therefore, mid to end of season moisture use is better correlated with seed yield, likely via improved HI, for the Canadian

Prairies. Early vigor and CGR may be important for improving seed yield and WUE of chickpea through reduction of soil evaporation and associated increase in transpiration (Tanner and Sinclair, 1983; Richards et al., 2002; Condon et al., 2002), particularly, in water-limited short-season production systems.

6.7. Conclusions

The results of this research suggest that the chickpea ideotype for the Canadian Prairies would have fern leaves and a bushy growth habit. Cultivars with fern leaves and bushy growth habits consistently performed better regarding maximum LI, maximum biomass accumulation, RI, HI, ascochyta blight severity and WUE_{seed} , resulting in higher seed yield. Higher PPD than currently recommended or a reduction in row spacing would also be required to enable greater maximum LI and biomass production for higher and stable seed yields on the short-season Canadian Prairies. Higher PPD also resulted in increased lowest pod height and no distinct negative effects on individual seed weight, ascochyta blight severity and HI.

6.8. Future Research

This research has revealed the superiority of cultivars with fern leaves over unifoliate leaves as well as cultivars with bushy growth habit over spreading and erect growth habits regarding growth and yield parameters, i.e., maximum LI, maximum biomass accumulation, RI, HI, WUE_{seed} and seed yield. The cultivars with fern leaves as well as those with bushy growth habits also showed significantly lower ascochyta blight severity at all but one growth stage-year.

Accumulation of LI over the growing season is important to biomass production (Monteith, 1977; Gallagher and Biscoe, 1978 and Thomson and Siddique, 1997) which is subsequently partitioned to seed yield. Maximum LI recorded in this research was 91% which implies that full canopy closure (95% maximum LI) was not attained under the conditions of research (i.e., seeding rates of 30 to 85 plants m^{-2} at 0.31 m row spacing). Increasing LI by identifying intra- and inter-row spacing for varying canopy types which maximizes LI may lead to seed yield improvement on the Canadian Prairies. Radiation interception increased about 30% by halving inter-row spacing while maintaining intra-row spacing in chickpea (Leach and Beech, 1988). Saccardo and Calcagno (1990) recommended 0.40, 0.25 and 0.12 inter-row spacing at 0.10 m

intra-row spacing for semi-prostrate, semi-erect and erect chickpea cultivars at PPDs of 24, 40 and 80 plants m⁻², respectively, under the Mediterranean conditions of Italy.

Significant differences in maximum LI were noted between leaf types and also amongst growth habits. Maximum LI also showed a positive correlation with seed yield in all but one location-year. The higher seed yield was attributed to greater light penetration into the fern canopy because of the more dissected nature of the pinnate leaves. In this research, light measurements were only obtained from above and below the canopy. Canopy light attenuation studies involving light measurements within the canopy could explain the mechanics of in-canopy light interception as to whether the greater maximum LI in the fern and bushy cultivars is associated with exposure of a larger leaf surface area to intercepted light.

Seasonal WU is the sum of transpiration and soil evaporation and WUE_{biomass} is improved by increasing transpiration while decreasing soil evaporation (Equation 5.2), especially in environments where crops depend on in-season precipitation like the Canadian Prairies. No treatment differences in WU were noted in this study but generally higher biomass accumulation in the fern leafed cultivars and also in the bushy and spreading cultivars was attributed to possible lower soil evaporation due to better soil shading and, therefore, higher transpiration. Water use was not partitioned into transpiration and soil evaporation in this study but may have to be studied to reveal whether different leaf types and growth habits do contribute to lower soil evaporation and higher transpiration through differences in soil shading capacity.

Early vigor is a highly desired trait in short-season production systems as it affords added advantages of rapid plant growth and early canopy closure to maximize seasonal light interception, reduction of evaporative water loss from the soil surface and limited weed growth. In this research, the low yielding unifoliate leaf cultivars and erect growth habit cultivars showed significantly higher early vigor over the high yielding fern and bushy cultivars, respectively. Genetic variation in early vigor of cultivars with fern leaf type and bushy growth habit may have to be explored to produce early vigor fern cultivars. Early vigor cultivars may also be achieved through larger seed size (Sabaghpour et al. 2003) or larger embryo size (Lopez-Castaneda et al.,

1996). Sabaghpour et al. (2003) reported an association between chickpea 100 seed-weight and early vigor.

This research, to date is the most comprehensive on chickpea on the Canadian Prairies comprising the most cultivars and the most location-years studied. Cultivars studied were, however, of varied genetic backgrounds and thus isogenic lines will have to be studied to reveal any genetic associations between both leaf type and growth habit and seed yield and ascochyta blight resistance under Canadian prairie conditions. The cultivar with spreading growth habit generally showed very low ascochyta blight severity and may be exploited in breeding programs for ascochyta blight resistance in chickpea. At ICRISAT-Patancheru, chickpea lines derived from a fern and unifoliate parent showed the fern trait produced significantly higher seed yield than the unifoliate trait (Srinivasan et al., 2006).

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8.0 APPENDICES

Appendix 1. Sample size and number of outliers of removed from analysis per variable per location-year in Chapter 3

Variable	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
Sample size	96	96	148	148	160	160	80
Plant stand	3	3	9	7	8	8	8
Max. node number			6	8	8	5	0
Plant height			6	10	5	0	4
Lowest pod height			7	8	9	0	7
Ascochyta severity (Early flower stage)	3		9		11		8
Ascochyta severity (Late pod stage)	4		9		9		5
Seed weight	4		9		9		8

SC Swift Current

STN Saskatoon

Appendix 2. Sample size and number of outliers of removed from analysis per variable per location-year in Chapter 4

Variable	2002		2003		2004		2005
	SC	STN	SC	STN	SC	STN	SC
Sample Size	96	96	148	148	160	160	80
Max. light interception	5	5	4	5	6	5	0
Cumulative intercepted radiation	5	4	2	3	6	6	0
Max. biomass	4	3	5	7	6	10	0
Seed yield	4	4	5	6	7	5	8
Harvest index	3	2	7	7	8	8	10

SC Swift Current
STN Saskatoon

Appendix 3. Sample size and number of outliers of removed from analysis per variable per location-year in Chapter 5

Variable	2003		2004	2005	
	Goodale	SPG	Goodale	Goodale	Swift Current
Sample size	48	48	48	48	48
Plant stand	1	4	5	2	3
Water use	1	2	2	2	1
Max. biomass	2	3	2	0	2
Seed yield	2	2	1	2	2
Water use efficiency (Biomass)	2	3	1	1	6
Water use efficiency (Seed yield)	2	2	2	1	2
Harvest index	2	1	1	2	2

Appendix 4. Analysis of variance for maximum node count on main stem of chickpea cultivars in Swift Current from 2003 to 2005 and Saskatoon from 2003 and 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Swift Current 2003</u>				<u>Saskatoon 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	124	35.98	<.0001	1	112	55.78	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	124	4.18	0.0431	1	112	6.37	0.0130
Erect vs. Spreading	1	124	16.41	<.0001	1	112	0.18	0.6729
Bushy vs. Spreading	1	124	5.35	0.0223	1	112	3.96	0.0489
<u>PPD</u>								
Actual PPD linear	1	124	9.06	0.0032	1	112	7.29	0.0080
Actual PPD quadratic	1	124	0.07	0.7960	1	112	0.03	0.8737
			<u>Swift Current 2004</u>				<u>Saskatoon 2004</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	141	39.70	<.0001	1	145	71.13	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	141	1.24	0.2676	1	145	1.64	0.2021
Erect vs. Spreading	1	141	0.03	0.8605	1	145	0.94	0.3340
Bushy vs. Spreading	1	141	0.86	0.3551	1	145	3.19	0.0761
<u>PPD</u>								
Actual PPD linear	1	141	2.71	0.1020	1	145	0.16	0.6884
Actual PPD quadratic	1	141	0.33	0.5693	1	145	17.33	<.0001
			<u>Swift Current 2005</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	71	17.20	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	71	0.60	0.4406				
Erect vs. Spreading	1	71	0.05	0.8290				
Bushy vs. Spreading	1	71	0.09	0.7658				
<u>PPD</u>								
Actual PPD linear	1	71	0.01	0.9082				
Actual PPD quadratic	1	71	0.23	0.0704				

Appendix 5. Analysis of variance for plant height at maturity of chickpea cultivars in Swift Current from 2003 to 2005 and Saskatoon from 2003 and 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value	
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	123	27.08	<.0001	1	112	3.39	0.0684	
<u>Growth habit</u>									
Erect vs. Bushy	1	123	0.00	0.9604	1	112	1.25	0.2667	
Erect vs. Spreading	1	123	166.73	<.0001	1	112	11.41	0.0010	
Bushy vs. Spreading	1	123	143.02	<.0001	1	112	14.86	0.0002	
<u>PPD</u>									
Actual PPD linear	1	123	0.59	0.4420	1	112	24.18	<.0001	
Actual PPD quadratic	1	123	1.47	0.2275	1	112	1.58	0.2118	
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	144	31.72	<.0001	1	69	0.94	0.3358	
<u>Growth habit</u>									
Erect vs. Bushy	1	144	0.73	0.3931	1	69	0.00	0.9869	
Erect vs. Spreading	1	144	34.93	<.0001	1	69	18.25	<.0001	
Bushy vs. Spreading	1	144	26.58	<.0001	1	69	17.65	<.0001	
<u>PPD</u>									
Actual PPD linear	1	144	23.93	<.0001	1	69	6.12	0.0159	
Actual PPD quadratic	1	144	1.46	0.2294	1	69	1.16	0.2843	
				<u>Swift Current 2005</u>					
<u>Leaf type</u>									
Fern vs. Unifoliate	1	145	0.11	0.7411					
<u>Growth habit</u>									
Erect vs. Bushy	1	145	0.11	0.7363					
Erect vs. Spreading	1	145	82.01	<.0001					
Bushy vs. Spreading	1	145	72.83	<.0001					
<u>PPD</u>									
Actual PPD linear	1	145	6.52	0.0117					
Actual PPD quadratic	1	145	0.27	0.6028					

Appendix 6. Analysis of variance for lowest pod height of chickpea cultivars in Swift Current from 2003 to 2005 and Saskatoon from 2003 and 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	122	156.30	<.0001	1	112	127.55	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	122	39.53	<.0001	1	112	20.80	<.0001
Erect vs. Spreading	1	122	90.67	<.0001	1	112	82.15	<.0001
Bushy vs. Spreading	1	122	19.74	<.0001	1	112	31.80	<.0001
<u>PPD</u>								
Actual PPD linear	1	122	10.60	0.0015	1	112	24.50	<.0001
Actual PPD quadratic	1	122	0.93	0.3362	1	112	0.21	0.6474
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	140	281.91	<.0001	1	69	54.52	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	140	71.23	<.0001	1	69	18.48	<.0001
Erect vs. Spreading	1	140	144.27	<.0001	1	69	17.33	<.0001
Bushy vs. Spreading	1	140	36.36	<.0001	1	69	1.52	0.2213
<u>PPD</u>								
Actual PPD linear	1	140	20.65	<.0001	1	69	3.88	0.0529
Actual PPD quadratic	1	140	9.83	0.0021	1	69	0.29	0.5916
				<u>Swift Current 2005</u>				
<u>Leaf type</u>								
Fern vs. Unifoliate	1	142	53.60	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	142	35.94	<.0001				
Erect vs. Spreading	1	142	132.45	<.0001				
Bushy vs. Spreading	1	142	51.60	<.0001				
<u>PPD</u>								
Actual PPD linear	1	142	15.22	0.0001				
Actual PPD quadratic	1	142	0.01	0.9431				

Appendix 7. Analysis of variance for ascochyta blight severity (percent Horsfall-Barratt scale) at early flower and late pod stages of chickpea cultivars in Swift Current from 2002 to 2005

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Early flower 2002</u>				<u>Late pod 2002</u>	
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	70	182.81	<.0001	1	69	129.27	<.0001
<u>PPD</u>								
Actual PPD linear	1	70	0.10	0.7527	1	69	2.61	0.1109
Actual PPD quadratic	1	70	0.02	0.8869	1	69	0.36	0.5498
			<u>Early flower 2003</u>				<u>Late pod 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	120	419.59	<.0001	1	121	40.83	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	120	75.98	<.0001	1	121	1.49	0.2239
Erect vs. Spreading	1	120	116.62	<.0001	1	121	40.79	<.0001
Bushy vs. Spreading	1	120	14.65	0.0002	1	121	45.05	<.0001
<u>PPD</u>								
Actual PPD linear	1	120	3.45	0.0658	1	121	13.72	0.0003
Actual PPD quadratic	1	120	4.76	0.0311	1	121	0.49	0.4839
			<u>Early flower 2004</u>				<u>Late pod 2004</u>	
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	138	383.55	<.0001	1	140	220.46	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	138	58.32	<.0001	1	140	24.53	<.0001
Erect vs. Spreading	1	138	88.18	<.0001	1	140	47.63	<.0001
Bushy vs. Spreading	1	138	15.21	0.0001	1	140	11.53	0.0009
<u>PPD</u>								
Actual PPD linear	1	138	16.18	<.0001	1	140	2.57	0.1111
Actual PPD quadratic	1	138	1.07	0.3033	1	140	2.04	0.1554
			<u>Early flower 2005</u>				<u>Late pod 2005</u>	
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	141	572.10	<.0001	1	144	798.72	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	141	55.96	<.0001	1	144	68.29	<.0001
Erect vs. Spreading	1	141	238.37	<.0001	1	144	338.24	<.0001
Bushy vs. Spreading	1	141	99.81	<.0001	1	144	149.72	<.0001
<u>PPD</u>								
Actual PPD linear	1	141	0.96	0.3296	1	144	1.57	0.2121
Actual PPD quadratic	1	141	3.26	0.0730	1	144	0.01	0.9345

Appendix 8. Analysis of variance for individual seed weight of chickpea cultivars in Swift Current from 2002 to 2005

Source of variation	Num d.f.	Den d.f.	F value	P value
<u>Swift Current 2002</u>				
<u>PPD</u>				
Actual PPD linear	1	69	23.43	<.0001
Actual PPD quadratic	1	69	2.80	0.0985
<u>Swift Current 2003</u>				
<u>PPD</u>				
Actual PPD linear	1	120	5.04	0.0266
Actual PPD quadratic	1	120	1.73	0.1908
<u>Swift Current 2004</u>				
<u>PPD</u>				
Actual PPD linear	1	140	49.73	<.0001
Actual PPD quadratic	1	140	18.25	<.0001
<u>Swift Current 2005</u>				
<u>PPD</u>				
Actual PPD linear	1	141	22.25	<.0001
Actual PPD quadratic	1	141	0.25	0.6192

Appendix 9. Analysis of variance for maximum light interception of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value	
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	65	205.70	<.0001	1	65	45.96	<.0001	
<u>PPD</u>									
Actual PPD linear	1	65	2.61	0.1109	1	65	0.45	0.5025	
Actual PPD quadratic	1	65	0.00	0.9509	1	65	3.33	0.0727	
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	125	6.32	0.0132	1	114	1.90	0.1710	
<u>Growth habit</u>									
Erect vs. Bushy	1	125	16.12	0.0001	1	114	0.00	0.9661	
Erect vs. Spreading	1	125	1.11	0.2931	1	114	0.37	0.5453	
Bushy vs. Spreading	1	125	3.36	0.0691	1	114	0.36	0.5510	
<u>PPD</u>									
Actual PPD linear	1	125	27.38	<.0001	1	114	0.00	0.9584	
Actual PPD quadratic	1	125	0.50	0.4824	1	114	2.77	0.0989	
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	140	275.58	<.0001	1	145	16.34	<.0001	
<u>Growth habit</u>									
Erect vs. Bushy	1	140	80.97	<.0001	1	145	1.70	0.1944	
Erect vs. Spreading	1	140	26.47	<.0001	1	145	2.03	0.1566	
Bushy vs. Spreading	1	140	1.22	0.2716	1	145	0.27	0.6035	
<u>PPD</u>									
Actual PPD linear	1	140	15.09	0.0002	1	145	1.89	0.1716	
Actual PPD quadratic	1	140	16.17	<.0001	1	145	0.23	0.6337	
				<u>Swift Current 2005</u>					
<u>Leaf type</u>									
Fern vs. Unifoliate	1	68	131.29	<.0001					
<u>Growth habit</u>									
Erect vs. Bushy	1	68	19.22	<.0001					
Erect vs. Spreading	1	68	47.07	<.0001					
Bushy vs. Spreading	1	68	14.14	0.0004					
<u>PPD</u>									
Actual PPD linear	1	68	18.89	<.0001					
Actual PPD quadratic	1	68	3.10	0.0827					

Appendix 10. Analysis of variance for cumulative intercepted radiation of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value	
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	60	41.09	<.0001	1	61	15.20	0.0002	
<u>PPD</u>									
Actual PPD linear	1	60	58.44	<.0001	1	61	38.60	<.0001	
Actual PPD quadratic	1	60	4.05	0.0486	1	61	2.98	0.0895	
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	119	5.95	0.0162	1	109	0.67	0.4161	
<u>Growth habit</u>									
Erect vs. Bushy	1	119	16.72	<.0001	1	109	2.52	0.1151	
Erect vs. Spreading	1	119	1.52	0.2208	1	109	9.56	0.0025	
Bushy vs. Spreading	1	119	15.91	0.0001	1	109	14.97	0.0002	
<u>PPD</u>									
Actual PPD linear	1	119	58.58	<.0001	1	109	23.70	<.0001	
Actual PPD quadratic	1	119	0.06	0.8146	1	109	1.74	0.1900	
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	113	36.53	<.0001	1	130	0.94	0.3350	
<u>Growth habit</u>									
Erect vs. Bushy	1	113	26.22	<.0001	1	130	1.08	0.3015	
Erect vs. Spreading	1	113	0.30	0.5870	1	130	0.06	0.8104	
Bushy vs. Spreading	1	113	9.48	0.0026	1	130	0.85	0.3576	
<u>PPD</u>									
Actual PPD linear	1	113	19.51	<.0001	1	130	49.02	<.0001	
Actual PPD quadratic	1	113	7.17	0.0085	1	130	0.06	0.8020	
				<u>Swift Current 2005</u>					
<u>Leaf type</u>									
Fern vs. Unifoliate	1	67	47.00	<.0001					
<u>Growth habit</u>									
Erect vs. Bushy	1	67	14.78	0.0003					
Erect vs. Spreading	1	67	8.14	0.0058					
Bushy vs. Spreading	1	67	0.08	0.7839					
<u>PPD</u>									
Actual PPD linear	1	67	0.24	0.6243					
Actual PPD quadratic	1	67	0.81	0.3720					

Appendix 11. Analysis of variance for maximum biomass of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	66	4.26	0.0429	1	67	0.62	0.4328
<u>PPD</u>								
Actual PPD linear	1	66	1.26	0.2650	1	67	1.43	0.2361
Actual PPD quadratic	1	66	0.03	0.8699	1	67	1.52	0.2216
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	122	0.37	0.5431	1	110	0.10	0.7573
<u>Growth habit</u>								
Erect vs. Bushy	1	122	11.56	0.0009	1	110	1.59	0.2104
Erect vs. Spreading	1	122	1.11	0.2937	1	110	0.17	0.6833
Bushy vs. Spreading	1	122	1.98	0.1623	1	110	0.17	0.6842
<u>PPD</u>								
Actual PPD linear	1	122	21.26	<.0001	1	110	1.92	0.1688
Actual PPD quadratic	1	122	0.08	0.7725	1	110	0.25	0.6190
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	140	4.48	0.0361	1	136	1.00	0.3181
<u>Growth habit</u>								
Erect vs. Bushy	1	140	23.09	<.0001	1	136	0.82	0.3670
Erect vs. Spreading	1	140	1.27	0.2623	1	136	6.26	0.0136
Bushy vs. Spreading	1	140	4.34	0.0391	1	136	8.96	0.0033
<u>PPD</u>								
Actual PPD linear	1	140	0.00	0.9945	1	136	0.99	0.3224
Actual PPD quadratic	1	140	8.42	0.0043	1	136	0.14	0.7088
				<u>Swift Current 2005</u>				
<u>Leaf type</u>								
Fern vs. Unifoliate	1	68	5.57	0.0212				
<u>Growth habit</u>								
Erect vs. Bushy	1	68	0.15	0.7018				
Erect vs. Spreading	1	68	0.23	0.6303				
Bushy vs. Spreading	1	68	0.05	0.8302				
<u>PPD</u>								
Actual PPD linear	1	68	2.40	0.1260				
Actual PPD quadratic	1	68	0.14	0.7099				

Appendix 12. Analysis of variance for radiation use efficiency radiation of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	63	0.00	0.9589	1	61	10.53	0.0019
<u>PPD</u>								
Actual PPD linear	1	63	30.25	<.0001	1	61	8.88	0.0041
Actual PPD quadratic	1	63	5.98	0.0173	1	61	2.07	0.1555
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	116	5.30	0.0232	1	104	2.56	0.1123
<u>Growth habit</u>								
Erect vs. Bushy	1	116	2.02	0.1581	1	104	3.54	0.0627
Erect vs. Spreading	1	116	1.12	0.2920	1	104	5.13	0.0256
Bushy vs. Spreading	1	116	0.00	0.9845	1	104	10.23	0.0018
<u>PPD</u>								
Actual PPD linear	1	116	9.42	0.0027	1	104	11.52	0.0010
Actual PPD quadratic	1	116	0.64	0.4252	1	104	8.50	0.0044
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	115	6.91	0.0097	1	41	3.98	0.0527
<u>Growth habit</u>								
Erect vs. Bushy	1	115	2.19	0.1415	1	41	5.80	0.0207
Erect vs. Spreading	1	115	1.15	0.2865	1	41	2.87	0.0980
Bushy vs. Spreading	1	115	4.51	0.0359	1	41	0.01	0.9237
<u>PPD</u>								
Actual PPD linear	1	115	13.34	0.0004	1	41	1.36	0.2507
Actual PPD quadratic	1	115	0.37	0.5456	1	41	1.16	0.2886
				<u>Swift Current 2005</u>				
<u>Leaf type</u>								
Fern vs. Unifoliate	1	64	1.13	0.2922				
<u>Growth habit</u>								
Erect vs. Bushy	1	64	1.30	0.2577				
Erect vs. Spreading	1	64	0.54	0.4646				
Bushy vs. Spreading	1	64	0.00	0.9868				
<u>PPD</u>								
Actual PPD linear	1	64	3.89	0.0530				
Actual PPD quadratic	1	64	0.35	0.5563				

Appendix 13. Analysis of variance for maximum light interception of chickpea cultivars as determined by spot and continuous measurements in Saskatoon in 2004 and Swift Current in 2005

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
	<u>Saskatoon 2004</u>				<u>Saskatoon 2004</u>			
	<u>(Spot)</u>				<u>(Continuous)</u>			
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	32	9.98	0.0035	1	15	2.19	0.1599
<u>Growth habit</u>								
Erect vs. Bushy	1	32	5.45	0.0259	1	15	0.76	0.3979
Erect vs. Spreading	1	32	13.77	0.0008	1	15	4.25	0.0570
Bushy vs. Spreading	1	32	4.00	0.0541	1	15	2.38	0.1435
<u>PPD</u>								
Actual PPD linear	1	32	0.49	0.4908	1	15	2.35	0.1463
Actual PPD quadratic	1	32	0.86	0.3617	1	15	0.24	0.6290
	<u>Swift Current 2005</u>				<u>Swift Current 2005</u>			
	<u>(Spot)</u>				<u>(Continuous)</u>			
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	32	139.28	<.0001	1	16	14.87	0.0014
<u>Growth habit</u>								
Erect vs. Bushy	1	32	102.59	<.0001	1	16	13.24	0.0022
Erect vs. Spreading	1	32	130.05	<.0001	1	16	15.12	0.0013
Bushy vs. Spreading	1	32	9.78	0.0037	1	16	0.13	0.7211
<u>PPD</u>								
Actual PPD linear	1	32	16.05	0.0003	1	16	18.53	0.0005
Actual PPD quadratic	1	32	1.38	0.2485	1	16	0.97	0.3391

Appendix 14. Analysis of variance for cumulative intercepted radiation of chickpea cultivars as determined by spot and continuous measurements in Saskatoon in 2004 and Swift Current in 2005

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
	<u>Saskatoon 2004</u> (Spot)				<u>Saskatoon 2004</u> (Continuous)			
<u>Leaf type</u>								
Fern vs. Unifoliate	1	15	3.35	0.0870	1	15	0.26	0.6152
<u>Growth habit</u>								
Erect vs. Bushy	1	15	3.44	0.0835	1	15	0.01	0.9103
Erect vs. Spreading	1	15	1.61	0.2244	1	15	1.95	0.1826
Bushy vs. Spreading	1	15	0.12	0.7341	1	15	3.00	0.1037
<u>PPD</u>								
Actual PPD linear	1	15	8.12	0.0122	1	15	29.48	<.0001
Actual PPD quadratic	1	15	0.48	0.4988	1	15	0.94	0.3480
	<u>Swift Current 2005</u> (Spot)				<u>Swift Current 2005</u> (Continuous)			
<u>Leaf type</u>								
Fern vs. Unifoliate	1	16	34.50	<.0001	1	16	6.19	0.0242
<u>Growth habit</u>								
Erect vs. Bushy	1	16	28.44	<.0001	1	16	6.32	0.0230
Erect vs. Spreading	1	16	28.44	<.0001	1	16	3.14	0.0953
Bushy vs. Spreading	1	16	0.81	0.3828	1	16	3.14	0.0953
<u>PPD</u>								
Actual PPD linear	1	16	48.73	<.0001	1	16	13.54	0.0020
Actual PPD quadratic	1	16	0.13	0.7247	1	16	0.02	0.8924

Appendix 15. Analysis of variance for radiation use efficiency of chickpea cultivars as determined by spot and continuous measurements in Saskatoon in 2004 and Swift Current in 2005

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
	<u>Saskatoon 2004</u> (Spot)				<u>Saskatoon 2004</u> (Continuous)			
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	13	0.03	0.8760	1	15	7.92	0.0131
<u>Growth habit</u>								
Erect vs. Bushy	1	13	0.12	0.7385	1	15	6.92	0.0189
Erect vs. Spreading	1	13	0.04	0.8502	1	15	5.36	0.0352
Bushy vs. Spreading	1	13	0.30	0.5948	1	15	0.04	0.8410
<u>PPD</u>								
Actual PPD linear	1	13	9.25	0.0094	1	15	21.77	0.0003
Actual PPD quadratic	1	13	0.68	0.4259	1	15	0.21	0.6567
	<u>Swift Current 2005</u> (Spot)				<u>Swift Current 2005</u> (Continuous)			
<u>Leaf type</u>								
Fern vs. Unifoliolate	1	15	1.59	0.2261	1	16	0.15	0.7007
<u>Growth habit</u>								
Erect vs. Bushy	1	15	1.21	0.2893	1	16	0.09	0.7675
Erect vs. Spreading	1	15	1.46	0.2454	1	16	0.19	0.6672
Bushy vs. Spreading	1	15	0.13	0.7212	1	16	0.05	0.8305
<u>PPD</u>								
Actual PPD linear	1	15	1.36	0.2620	1	16	2.13	0.1636
Actual PPD quadratic	1	15	3.20	0.0940	1	16	0.18	0.6735

Appendix 16. Analysis of variance for seed yield of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	65	392.17	<.0001	1	65	9.49	<.0001
<u>PPD</u>								
Actual PPD linear	1	65	72.22	<.0001	1	65	11.62	0.0011
Actual PPD quadratic	1	65	26.17	<.0001	1	65	1.68	0.1991
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	121	75.50	<.0001	1	110	54.06	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	121	29.10	<.0001	1	110	7.75	0.0063
Erect vs. Spreading	1	121	0.02	0.9023	1	110	8.21	0.0050
Bushy vs. Spreading	1	121	15.65	0.0001	1	110	0.82	0.3683
<u>PPD</u>								
Actual PPD linear	1	121	11.29	0.0010	1	110	0.43	0.5158
Actual PPD quadratic	1	121	0.00	0.9914	1	110	2.53	0.1145
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>		
<u>Leaf type</u>								
Fern vs. Unifoliate	1	139	1234.12	<.0001	1	128	281.24	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	139	375.76	<.0001	1	128	124.95	<.0001
Erect vs. Spreading	1	139	90.65	<.0001	1	128	72.35	<.0001
Bushy vs. Spreading	1	139	11.09	0.0011	1	128	0.32	0.5726
<u>PPD</u>								
Actual PPD linear	1	139	91.75	<.0001	1	128	10.02	0.0019
Actual PPD quadratic	1	139	37.68	<.0001	1	128	2.64	0.1064
				<u>Swift Current 2005</u>				
<u>Leaf type</u>								
Fern vs. Unifoliate	1	138	627.58	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	138	192.37	<.0001				
Erect vs. Spreading	1	138	166.56	<.0001				
Bushy vs. Spreading	1	138	12.90	0.0005				
<u>PPD</u>								
Actual PPD linear	1	138	12.51	0.0006				
Actual PPD quadratic	1	138	1.33	0.2503				

Appendix 17. Analysis of variance for harvest index of chickpea cultivars in Swift Current from 2002 to 2005 and Saskatoon from 2002 to 2004

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value	
				<u>Swift Current 2002</u>		<u>Saskatoon 2002</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	69	11.06	0.0014	1	69	32.12	<.0001	
<u>PPD</u>									
Actual PPD linear	1	69	0.59	0.4448	1	69	1.13	0.2913	
Actual PPD quadratic	1	69	1.66	0.2021	1	69	0.95	0.3343	
				<u>Swift Current 2003</u>		<u>Saskatoon 2003</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	121	650.18	<.0001	1	109	198.42	<.0001	
<u>Growth habit</u>									
Erect vs. Bushy	1	121	75.57	<.0001	1	109	96.24	<.0001	
Erect vs. Spreading	1	121	72.24	<.0001	1	109	21.40	<.0001	
Bushy vs. Spreading	1	121	3.08	0.0820	1	109	4.40	0.0382	
<u>PPD</u>									
Actual PPD linear	1	121	14.12	0.0003	1	109	0.32	0.5750	
Actual PPD quadratic	1	121	0.77	0.3814	1	109	0.56	0.4573	
				<u>Swift Current 2004</u>		<u>Saskatoon 2004</u>			
<u>Leaf type</u>									
Fern vs. Unifoliate	1	141	550.39	<.0001	1	127	176.87	<.0001	
<u>Growth habit</u>									
Erect vs. Bushy	1	141	135.99	<.0001	1	127	33.04	<.0001	
Erect vs. Spreading	1	141	78.33	<.0001	1	127	73.76	<.0001	
Bushy vs. Spreading	1	141	0.68	0.4120	1	127	20.73	<.0001	
<u>PPD</u>									
Actual PPD linear	1	141	16.57	<.0001	1	127	0.53	0.4697	
Actual PPD quadratic	1	141	7.55	0.0068	1	127	1.92	0.1678	
				<u>Swift Current 2005</u>					
<u>Leaf type</u>									
Fern vs. Unifoliate	1	138	399.28	<.0001					
<u>Growth habit</u>									
Erect vs. Bushy	1	138	180.66	<.0001					
Erect vs. Spreading	1	138	43.79	<.0001					
Bushy vs. Spreading	1	138	6.22	0.0138					
<u>PPD</u>									
Actual PPD linear	1	138	1.95	0.1653					
Actual PPD quadratic	1	138	0.03	0.8666					

Appendix 18. Analysis of variance for water use of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Goodale 2003</u>				<u>SPG 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	9.38	0.0046	1	31	0.04	0.8441
<u>Growth habit</u>								
Erect vs. Bushy	1	30	1.88	0.1801	1	31	0.47	0.4968
Erect vs. Spreading	1	30	4.92	0.0343	1	31	0.20	0.6564
Bushy vs. Spreading	1	30	1.78	0.1927	1	31	0.01	0.9373
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	0.67	0.4183	1	31	0.60	0.4437
			<u>Goodale 2004</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	31	5.31	0.0280				
<u>Growth habit</u>								
Erect vs. Bushy	1	31	3.35	0.0770				
Erect vs. Spreading	1	31	1.72	0.1991				
Bushy vs. Spreading	1	31	8.01	0.0081				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	31	3.23	0.0820				
			<u>Goodale 2005</u>		<u>Swift Current 2005</u>			
<u>Leaf type</u>								
Fern vs. Unifoliate	1	23	5.74	0.0252	1	32	1.50	0.2300
<u>Growth habit</u>								
Erect vs. Bushy	1	23	8.36	0.0082	1	32	3.17	0.0847
Erect vs. Spreading	1	23	0.70	0.4130	1	32	0.82	0.3711
Bushy vs. Spreading	1	23	13.58	0.0012	1	32	0.21	0.6475
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	23	0.39	0.5363	1	32	2.53	0.1214

Appendix 19. Analysis of variance for maximum biomass of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Goodale 2003</u>				<u>SPG 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	5.08	0.0317	1	30	4.46	0.0431
<u>Growth habit</u>								
Erect vs. Bushy	1	30	0.63	0.4353	1	30	0.15	0.7048
Erect vs. Spreading	1	30	0.51	0.4820	1	30	0.37	0.5493
Bushy vs. Spreading	1	30	0.01	0.9117	1	30	0.13	0.7215
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	0.91	0.3468	1	30	1.78	0.1924
			<u>Goodale 2004</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	1.51	0.2293				
<u>Growth habit</u>								
Erect vs. Bushy	1	30	5.06	0.0320				
Erect vs. Spreading	1	30	3.88	0.0582				
Bushy vs. Spreading	1	30	15.39	0.0005				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	0.62	0.4361				
			<u>Goodale 2005</u>				<u>Swift Current 2005</u>	
Fern vs. Unifoliate	1	25	0.43	0.5170	1	30	0.15	0.7037
<u>Leaf type</u>								
<u>Growth habit</u>								
Erect vs. Bushy	1	25	0.19	0.6685	1	30	4.10	0.0518
Erect vs. Spreading	1	25	1.38	0.2507	1	30	0.39	0.5361
Bushy vs. Spreading	1	25	0.83	0.3706	1	30	2.42	0.1302
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	25	2.19	0.1515	1	30	0.00	0.9657

Appendix 20. Analysis of variance for seed yield of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Goodale 2003</u>				<u>SPG 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	29	28.03	<.0001	1	31	378.83	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	29	52.78	<.0001	1	31	187.30	<.0001
Erect vs. Spreading	1	29	15.55	0.0005	1	31	120.33	<.0001
Bushy vs. Spreading	1	29	10.22	0.0033	1	31	0.23	0.6322
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	29	4.10	0.0523	1	31	2.46	0.1268
			<u>Goodale 2004</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	27	124.85	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	27	88.72	<.0001				
Erect vs. Spreading	1	27	25.83	<.0001				
Bushy vs. Spreading	1	27	6.45	0.0171				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	27	17.75	0.0003				
			<u>Goodale 2005</u>				<u>Swift Current 2005</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	22	55.44	<.0001	1	31	150.22	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	22	22.31	0.0001	1	31	54.68	<.0001
Erect vs. Spreading	1	22	66.85	<.0001	1	31	43.02	<.0001
Bushy vs. Spreading	1	22	23.98	<.0001	1	31	0.93	0.3426
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	22	0.40	0.5354	1	31	7.39	0.0107

Appendix 21. Analysis of variance for water use efficiency for biomass of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
	<u>Goodale 2003</u>				<u>SPG 2003</u>			
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	0.11	0.7392	1	33	3.11	0.0871
<u>Growth habit</u>								
Erect vs. Bushy	1	30	0.00	0.9584	1	33	1.26	0.2696
Erect vs. Spreading	1	30	0.06	0.8064	1	33	0.77	0.3876
Bushy vs. Spreading	1	30	0.10	0.7523	1	33	0.00	0.9676
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	1.24	0.2752	1	33	0.78	0.3833
	<u>Goodale 2004</u>							
<u>Leaf type</u>								
Fern vs. Unifoliate	1	32	2.65	0.1136				
<u>Growth habit</u>								
Erect vs. Bushy	1	32	0.40	0.5331				
Erect vs. Spreading	1	32	0.00	0.9974				
Bushy vs. Spreading	1	32	0.25	0.6228				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	32	0.27	0.6093				
	<u>Goodale 2005</u>				<u>Swift Current 2005</u>			
<u>Leaf type</u>								
Fern vs. Unifoliate	1	25	3.16	0.0875	1	32	0.00	0.9550
<u>Growth habit</u>								
Erect vs. Bushy	1	25	1.47	0.2367	1	32	1.15	0.2919
Erect vs. Spreading	1	25	0.73	0.4026	1	32	0.88	0.3539
Bushy vs. Spreading	1	25	0.02	0.8804	1	32	3.39	0.0750
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	25	1.51	0.2309	1	32	0.91	0.3461

Appendix 22. Analysis of variance for water use efficiency for seed yield of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Goodale 2003</u>				<u>SPG 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	27	19.03	0.0002	1	30	49.73	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	27	22.55	<.0001	1	30	24.45	<.0001
Erect vs. Spreading	1	27	3.92	0.0579	1	30	16.61	0.0003
Bushy vs. Spreading	1	27	2.92	0.0990	1	30	0.08	0.7752
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	27	2.20	0.1497	1	30	0.60	0.4445
			<u>Goodale 2004</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	26	60.45	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	26	33.17	<.0001				
Erect vs. Spreading	1	26	19.77	0.0001				
Bushy vs. Spreading	1	26	0.04	0.8511				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	26	16.98	0.0003				
			<u>Goodale 2005</u>				<u>Swift Current 2005</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	23	30.94	<.0001	1	31	104.49	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	23	15.72	0.0006	1	31	45.03	<.0001
Erect vs. Spreading	1	23	23.94	<.0001	1	31	29.76	<.0001
Bushy vs. Spreading	1	23	3.08	0.0925	1	31	0.13	0.7225
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	23	3.40	0.0782	1	31	7.35	0.0108

Appendix 23. Analysis of variance for harvest index of chickpea cultivars at Goodale (2003 to 2005), SPG (2003) and Swift Current (2005)

Source of variation	Num d.f.	Den d.f.	F value	P value	Num d.f.	Den d.f.	F value	P value
			<u>Goodale 2003</u>				<u>SPG 2003</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	159.80	<.0001	1	29	70.75	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	30	39.33	<.0001	1	29	11.72	0.0019
Erect vs. Spreading	1	30	82.09	<.0001	1	29	39.50	<.0001
Bushy vs. Spreading	1	30	20.20	<.0001	1	29	15.42	0.0005
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	15.05	0.0005	1	29	2.96	0.0960
			<u>Goodale 2004</u>					
<u>Leaf type</u>								
Fern vs. Unifoliate	1	30	69.62	<.0001				
<u>Growth habit</u>								
Erect vs. Bushy	1	30	2.86	0.1013				
Erect vs. Spreading	1	30	5.75	0.0229				
Bushy vs. Spreading	1	30	1.81	0.1885				
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	30	2.83	0.1031				
			<u>Goodale 2005</u>				<u>Swift Current 2005</u>	
<u>Leaf type</u>								
Fern vs. Unifoliate	1	23	104.65	<.0001	1	31	353.25	<.0001
<u>Growth habit</u>								
Erect vs. Bushy	1	23	11.48	0.0025	1	31	84.21	<.0001
Erect vs. Spreading	1	23	64.85	<.0001	1	31	59.32	<.0001
Bushy vs. Spreading	1	23	32.99	<.0001	1	31	0.55	0.4620
<u>PPD (plants m⁻²)</u>								
45 vs. 75	1	23	3.18	0.0876	1	31	0.12	0.7342