Performance of Kabuli Chickpea Cultivars with the Fern and Unifoliate Leaf Traits in Saskatchewan

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Abstract

Kabuli chickpea (*Cicer arietinum* L.) has two leaf types, the fern and unifoliate. Yield potential is limited for kabuli chickpea in Saskatchewan. It is limited by a short-season, a semi-arid environment, and end-of-season rainfall. Manipulating plant population, and choosing chickpea cultivars with the best leaf type for biomass production, radiation interception and yield for the early, middle, or late growth season, may increase chickpea yield. Therefore, the objectives of this study were: to (i) determine the relationship between leaf type and key growth parameters of six chickpea cultivars varying in leaf morphology at moderate and high plant population densities; (ii) to characterize the reaction of the fern and unifoliate leaf to altered canopy light environments. Different light environments were created by 50% defoliation at vegetative growth, first flower, and 50% shading from vegetative growth to first flower, as well as two light enrichment treatments initiated at the first flower and pod formation stages.

Fern leaf cultivars exhibited higher maximum light interception, seasonal cumulative intercepted radiation and a higher harvest index compared to unifoliate leaf cultivars. However, both leaf type canopies had less than 95% light interception for most of the season. The fern and unifoliate leaf type contributed to similar radiation use efficiency in three out of four location-years. In addition, fern leaf cultivars produced significantly higher seed yield than cultivars with unifoliate leaves.

Plant density influenced growth parameters. For example, the 45 plants m^{-2} treatment had a higher harvest index than the 85 plants m^{-2} treatment, in two

location-years, while both population treatments were similar in the other two location-years. Yield of chickpea was increased by higher plant population in only one location-year, but was not significantly affected by plant population in the other location-years. The effect of canopy light environment manipulation on chickpea yield depended on the stages of plant development when they were applied. Defoliation at vegetative growth and first flower had no effect on yield. However, plants responded significantly to the 50% shade treatment; the crop growth rate, harvest index and yield were less in the shaded treatment compared to the control. Shading also increased plant height. Light enrichment treatments increased the yield. However, the degree of yield increase was greater when light enrichment occurred at first flower, than at the later stage of pod formation. These results highlighted the importance of the amount of irradiance during the flowering stage.

It was concluded that chickpea breeders should select lines with fern leaves for improved radiation interception when breeding cultivars for semiarid short-season environments such as in Saskatchewan. Management and breeding practices should ensure that the crop can make efficient use of the solar radiation at flowering to maximize yield. Improvement at the canopy and subsequent yield level is yet to be made in Saskatchewan environments by increased light interception, increased growth before flowering, and increased and stable harvest index.

Acknowledgements

This thesis is dedicated to my family, especially my parents Yunxiang Li and Suwen Zhao, for their love and passion for life, nature and agriculture, and their belief in the value of higher education.

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List of Abbreviations

CGR   Crop growth rate

DAS   Days after seeding

FLWDEF   Defoliation at first flower stage

FLWENR   Light enrichment initiated at first flower stage

HI   Harvest index

LAI   Leaf area index

LP   Lowest pod

LSD   Least significant difference

PAR   Photosynthetically active radiation

PODENR   Light enrichment initiated at pod formation stage

PPD   Plant population density

RUE   Radiation use efficiency

SHADE   Shading from vegetative stage to first flower stage

VEGDEF   Defoliation at vegetative stage

1.0 Introduction

Chickpea (*Cicer arietinum L.*) is a self-pollinated, diploid, annual grain legume. The total world production of grain legumes is about 56.5 million tonnes per annum (FAO, 2004). Dry bean (*Phaseolus vulgaris L.*) at 19.0 million tonnes ranks first, followed by field pea (*Pisum sativa L.*) at 10.3 million tonnes, and chickpea with 7.1 million tonnes (FAO, 2004). Chickpea seed is a major source of high-quality protein and carbohydrates in human diets. Chickpea maintains soil fertility, through biological nitrogen fixation (Gan et al., 2005) and contributes to the agricultural sustainability of cropping systems in cereal-legume rotations (Miller et al., 2002).

Several morphological characters are used for classification of chickpea into two main market classes. The desi type, grown mainly in the Indian subcontinent, Iran and Ethiopia, is characterized by pink flowers and small (180-300 mg) usually angular, yellow-brown colored seeds. Desi cultivars account for about 85% of the world's total production of chickpea. The kabuli type is grown in countries of the Mediterranean region, West Asia and North Africa, Mexico and more recently in Australia and North America (FAO, 2004). It possesses white flowers and large (200-680 mg) smooth, or wrinked, light-colored seeds. Both desi and kabuli type chickpea currently are grown in the Northern Great Plains.

Kabuli chickpea has several leaf types, including narrow leaflets, tiny leaflets and bipinnate leaf, two of which are the fern leaf and unifoliate leaf. The

fern leaf is most common internationally. The unifoliate leaf trait is controlled by a single gene (Muehlbauer and Singh, 1987). Multiple leaflets attached to a petiole characterize the fern leaf, while the unifoliate leaf is a single large leaf attached to the petiole. The unifoliate leaf type is associated with reduced resistance to ascochyta blight, a fungal disease caused by *Ascochyta rabiei* (Pass.) Labrousse (Gan et al., 2003a). In some production area, the fern leaf trait may increase the green leaf area duration, compared to the unifoliate trait (Anwar et al., 2003a). Currently, ten kabuli chickpea cultivars are grown in Saskatchewan, which include five fern-leaf cultivars (Amit, CDC ChiChi, CDC Yuma, CDC Chico, CDC Frontier) and five unifoliate-leaf cultivars (Sanford, CDC Diva, CDC Xena, Dwelley, Evans).

The main abiotic problem associated with chickpea production in Saskatchewan is the short growing season. Chickpea grown in the short growing season may produce inadequate leaf area, compared to chickpea grown in areas with a longer growing season. The highly variable and unpredictable precipitation (Padbury et al., 2002) in August and September, may cause the indeterminate chickpea to keep growing, and fail to complete its life cycle before the onset of frost.

Efficient utilization of available solar radiation is an important factor in improving productivity, while radiation interception is strongly affected by crop canopy structure. Increasing plant population densities has been investigated by many chickpea researchers as a way of improving interception of incoming solar radiation by chickpea canopies. Physiologists have used high plant population densities as a technique to increase crop yield per unit area in short-season soybean (Ball et al., 2000). Agronomists have estimated the optimum plant population

densities in Saskatchewan without considering maximizing the total solar radiation

intercepted by the chickpea canopy. Thus, the best combination of leaf morphology

and plant population density may utilize the solar radiation maximally and increase

chickpea yield in Saskatchewan. The hypothesis of this thesis was that the fern leaf

has greater leaf area, results in quicker canopy closure, and has a higher light

interception compared with the unifoliate leaf. If a higher plant population than

currently recommended is used, this would increase seasonal cumulative intercepted

radiation and result in higher yield potential. Moreover, one leaf type may be more

capable to utilize greater available solar radiation at a particular stage of crop

growth, and result in a different rate of plant growth and yield formation. In this

thesis, the following key questions were addressed:

(1) Which leaf type, fern or unifoliate, is superior for biomass production, radiation

interception and yield, in the short-growing season?

(2) What plant population densities in combination with leaf type, are most suitable

for biomass production, radiation interception and yield production in Saskatchewan?

(3) Which leaf type, fern or unifoliate, is superior for biomass production, and

radiation interception and yield, during the early, middle or late portion of the

growing season?

(4) What effect does defoliation, shading and light enrichment have on kabuli

chickpea growth, and yield production?

Answers to questions one and two can provide information for chickpea

breeders and producers on the recommendations of plant population densities that

are most suited for Saskatchewan, as well as the best leaf trait for future chickpea

cultivars. By determining which leaf type is superior, chickpea breeders and crop physiologists can elucidate the best leaf trait for early, middle, and late season growth and development. Determining the effect of defoliation would reveal the critical period for chickpea growth and yield formation, so producers could maximize crop management within this period to maximize yield potential. The results of this study should contribute to a more thorough understanding of kabuli chickpea production in the short growing season of Saskatchewan.

2.0 Literature Review

Chickpea (*Cicer arietinum* L.) is one of the world's most important grain legumes whose seed is a major source of plant-based dietary protein and carbohydrates. World chickpea production has increased steadily in the past two decades, and in 2003 production reached 7.1 million tonnes, the third highest ranked pulse crop behind dry bean (*Phaseolus vulgaris* L.) at 19.0 million tonnes, and field pea (*Pisum sativum* L.) at 10.3 million tonnes (FAO, 2004). Two commercial types of chickpea are generally grown; the kabuli chickpea in the Mediterranean and Near East region, and the desi chickpea in the Indian subcontinent and East Africa (Kumar and Abbo, 2001).

This drought-tolerant, cool season legume is a relatively new crop in the Northern Great Plains, and the crop is grown mainly in the Brown (Aridic Haploborolls) and Dark Brown (Typic Borolls) soil zones of Saskatchewan, Alberta and the northern United States. The introduction of chickpea has contributed to increased crop diversification away from wheat-based production in these regions. The crop has also enhanced environmental sustainability due to its nitrogen fixation ability and rotational benefit, all of which facilitate higher cropping intensification (Miller et al., 2002). Both desi and kabuli chickpea are produced in these regions. Desi chickpea is characterized by pink flowers and small, (180 to 300 mg) angular and yellow-brown colored seeds. The kabuli chickpea are also known as garbanzo

beans, possess white flowers and have a large (200 to 680 mg), cream-colored seed with a thin seed coat.

2.1 Semi-arid short growing season

In the semi-arid Northern Great Plains, the climate is characterized by a short and warm summer, followed by a long and cold winter. Mean annual temperature ranges from -0.2 ^{o}C to 10.9 ^{o}C, with large diurnal ranges in air temperature. This includes highly variable and unpredictable precipitation in August and September (Padbury et al., 2002). Total precipitation from April to July is typically between 165 mm and 302 mm. Annual precipitation ranges from 254 to 599 mm. The frost-free season, can be as long as 157 days in South Dakota, and as short as 83 days in northern Alberta. These types of climatic conditions often cause the indeterminate chickpea crop to continue growing, without completing its life cycle before the onset of fall frost. Seasonal fluctuation of environment may influence crop growth pattern and cause yield variation.

2.2 Main factors limiting kabuli chickpea growth

There are many factors that affect the growth and development of chickpea in the northern Great Plains. The major constraints are the short growing season and fungal diseases. The average frost-free period (0 ^{o}C basis) ranges from 92 to 120 days in this region (Cutforth et al., 1993). This is close to the minimum requirements for the growth and development of chickpea plants. Chickpea production in the last few years has been reduced by ascochyta blight caused by *Ascochyta rabiei* (Pass.) Labrousse (Nene and Reddy, 1987). The fungus is well

established in many local chickpea fields, seed lots, crop residues, and volunteer

chickpea plants. This disease caused chickpea yield losses in Saskatchewan of 25%

in 2000 and 30% in 2001 (Gan et al., 2003a).

2.3 The use of biomass and harvest index as a function of seed yield

Seed yield produced by a crop is a function of biomass and harvest index (HI)

(Donald, 1968). Changes either in HI or biomass accumulation, or both, can affect

yield. Singh et al. (1990) using path coefficient analysis demonstrated that biomass

and HI were the major contributors to chickpea seed yield. Crop growth rate (CGR)

is a prime factor in determining seed yield because it reflects the capacity of

assimilate and affects dry matter accumulation. There is a close association between

maximum dry matter production and maximum CGR (Ball et al., 2000).

Verghis et al. (1999) found that the CGR and the duration of the phase where

growth is linear are both influenced by the variability in maximum biomass

production in chickpea. In Northern India, CGR and the rate of partitioning of

biomass to seeds, exhibited a positive relationship under drought stress

(Krishnamurthy et al., 1999). Another study conducted in Northern India, showed

that the major source of yield variation among 120 chickpea genotypes, was CGR

rather than the variation in duration of reproductive growth or HI (Williams and

Saxena, 1991). They also found that the HI and the duration of vegetative growth

were negatively related to CGR. However, they did not give any specific

physiological reason for this variation. Under reduced light intensity like shading,

chickpea produced less maximum biomass with a reduced CGR (Verghis et al.,

1999).

The HI of legumes, is much less stable than that of cereal crops (Verghis et al, 1999). Shading plants also caused a significantly lower HI, which was a result of increased level of reproductive site abortion. Furthermore, HI seemed to be related to the soil water status. Harvest index decreased under terminal drought (Leport et al., 2006). In contrast, HI was significantly higher for chickpea irrigated during flowering to podding in a cool-temperate subhumid climate, compared to dryland chickpea (Anwar et al., 2003a). But response of HI to plant population density was inconsistent and varied with environment; in a year without water stress, HI increased with increasing population density, but in a year with water stress, HI tended to be constant or declined with increasing population density (Ayaz et al., 2004).

2.4 The use of radiation use efficiency, intercepted radiation and harvest index as a function of seed yield

Yield production by a crop is a function of the amount of solar radiation intercepted by the canopy, the rate of conversion of intercepted light into biomass (radiation use efficiency), and HI (Sinclair and Gardner, 1998). Information on radiation use efficiency (RUE) for grain legumes such as soybean and peanut is abundant, but published information on RUE values for chickpea (Table 2.1) is scarce. Published RUE values for chickpea (Table 2.1) are within the range of values obtained for other legumes evaluated in diverse field sites. Therefore, a factor of 0.45 or 0.50 has been used to convert total solar radiation into photosynthetically active radiation (PAR). The lowest RUE was for a drought-stressed study in northern Syria. Three other studies had the relatively high values

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Table 2.1 Chickpea radiation use efficiency in various locations in the literature.

Source	Location	Radiation PAR or Solar	Radiation use efficiency (g MJ $^{-1}$ on a PAR basis)	Comments
Albrizio and Stedut (2005)	Italy	Solar	1.20	Difference between C_3 and C_4 species
Ayaz et al. (2004)	Canterbury, New Zealand	PAR	1.10-1.50	Population and species differences
Anwar et al. (2003a)	Canterbury, New Zealand	PAR	0.92-1.46	Difference in sowing date and irrigation
Thomas and Fukai (1995)	South-eastern Queensland, Australia	PAR	0.91-1.15	Water stress during leaf area expansion with little adverse effect on RUE
Singh and Sri Rama (1989)	Hyderabad, Indian	Solar	0.55-0.67	RUE decreased with the decrease in soil water content
Leach and Beech (1988)	South-eastern Queensland, Australia	PAR	1.13-1.53	Difference in row spacing and plant population
Hughes et al. (1987)	Northern Syria	Solar	0.30-0.93	Difference in planting date, plant population and growth habit

for RUE because irrigation and water treatments were applied. Ayaz et al. (2004) compared the RUE among four legumes including desi chickpea in New Zealand and found that the species with highest yield also had the highest RUE. However, Thomson and Siddique (1997), found that differences among species in RUE was poorly correlated with maximum biomass in a Mediterranean-type environment in Australia. Singh and Sri Rama (1989) reported that water deficit occurring during the growth stages prior to pod filling decreased the RUE of chickpea in India and suggested that RUE should be related to plant water status. Leach and Beach (1988), found that with increasing row width RUE increased, although responses of RUE to plant population density were inconsistent. Hughes et al. (1987) found that RUE was greater for erect growth habit types than prostrate growth habit types, and they also reported that RUE was less for a high plant population density treatment (60 plants m^{-2}) compared to a low plant population density (30 plants m^{-2}) treatment. In a cool-temperate subhumid climate, RUE of kabuli chickpea increased as population increased from 50 to 100 plants m^{-2} (Ayaz et al., 2004). To date, there is no study comparing differences in RUE among chickpea genotypes differing in leaf type from any region.

Researches also have manipulated the radiation interception of chickpea. In a tropical environment, chickpea plant height and branch number per plant were higher as radiation levels were reduced (Miah et al., 2003). Reduced incident solar radiation by cloudy weather caused abortion of reproductive structures and yield reduction (Hay and Walker, 1989). In a cool temperate subhumid climate, low solar radiation resulted in a desi chickpea crop producing less seed (Hernandez, 1986).

Shading reduced the level of incident and the subsequent intercepted radiation (Saxena and Sheldrake, 1980; Hughes et al., 1987). It also reduced the number of pods and the amount of nitrogen accumulation in soybean (*Glycine max*. (L.) Merr) (Jiang and Egli, 1993). In contrast, Allen (1975) reported that reduced exposure to sunlight by 30% was favorable during excessively hot days around solar noon, because soil and air temperature, wind speed and soil water use were all reduced.

2.5 Strategies to maximize the yield potential of kabuli chickpea

2.5.1 Seeding dates

The most important step towards maximizing yields of chickpea is to ensure that the phenology of the crop fits the constraints of the production environment, i.e., climate, latitude and crop management (Summerfield et al., 1990). In the cool climate of western Canada, planting in early spring (late April) when soil temperatures are cool, results in poor crop establishment. Also cold soils increase susceptibility to soil-borne pathogens, delay seedling emergence and reduce seedling vigor (Auld et al., 1988; Croser et al., 2003; Gan et al., 2002). Delayed sowing can reduce flower and pod abortion, when flowering occurs in hot July periods. Seed yield is often limited by a shorter growing season and late-season frost. The short season and early frosts are more damaging and result in pod abortion and large reductions in yield (Croser et al., 2003).

Early seeding would take advantage of early flowering and result in higher yield potential in a short growing season. This has been demonstrated by early sown chickpea intercepting more radiation, compared to later sown crops (Anwar et al., 2003a). With adequate moisture, early seeding results in rapid emergence,

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higher fertile pod production, higher yield, a longer reproductive growth phase, and more heat units accumulated in the growing season for seed formation (Gan et al., 2002). In Saskatchewan, chickpea should be planted in early May when soil temperatures in a10-cm depth approach 9 to 10 $^{\circ}$C (Gan et al., 2002)

2.5.2 Plant population density

Management practices such as narrow row spacing and high plant population can increase the light interception of chickpea (Leach and Beech, 1988; Ayaz et al., 2004). Several experiments have evaluated optimal chickpea plant population in different production systems. In the Mediterranean–type environment of south-western Australia, seed yield of kabuli chickpea increased when plant population increased from 12 to 60 plants m^{-2} (Jettner et al., 1999). Recent studies in a short-season Mediterranean-type environment, showed a positive association between plant population and seed yield (Regan et al., 2003). In Canada, yield increased with increasing plant population from 20 to 50 plants m^{-2} on summerfallow at Swift Current, on a Brown Chernozen soil. When grown on wheat stubble, yield increased as plant population increased, but only to a certain point due to the lower water availability when grown on stubble (Gan et al., 2002). However, in a cool-temperate subhumid climate in New Zealand, increasing the plant population from 15 to 60 plants m^{-2} resulted in significant reductions in both total dry matter and seed yield (McKenzie and Hill, 1995). These researchers reported that light interception was greater at higher plant populations; the crops had lower growth efficiency, because plants had fewer young leaves for photosynthesis during reproductive growth (Hernandez and Hill, 1985).

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Currently, the recommended plant population density for kabuli chickpea in Saskatchewan is 45 to 50 plants m^{-2} (Gan et al., 2003b). However, these recommendations did not consider the potential of increasing light interception by altering plant canopy structure. Plant populations higher than the current recommendation may be needed to ensure rapid canopy closure and full light interception of canopy. Higher plant population can result in earlier canopy closure in kabuli chickpea (Ayaz et al., 2004), soybean (Ball et al., 2000; Purcell et al., 2002), fababean (Loss et al., 1998), and lentil (Mckenzie and Hill, 1991). Besides increased radiation interception and canopy closure, high plant population can suppress weeds, minimize soil surface evaporation, and increase harvest height and lowest pod height for combine harvest and accelerate maturity (Siddique and Sedgley, 1987; Beech and Leach, 1988; and Jettner et al., 1999; Gan et al., 2002). In contrast, in northern Syria, plant population and growth habits had relatively small effects on dry matter production. The series of chickpea field experiments mentioned above, involved a limited number of cultivars and canopy architecture; therefore, information is lacking on the effect of different canopy types on plant population density.

2.5.3 Best leaf type to maximize utilization of solar radiation

Donald (1968) suggested breeding for yield improvement of a species in a particular type of environment by selecting for physiological and morphological traits is conducive to high yields in that environment. The ideal kabuli chickpea for a short growing season should have a rapid development of initial leaf area for high light interception and maximum canopy coverage to exploit the available light, for

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as long as possible, coupled with a high CGR for canopy assimilation. Different leaf shapes and sizes can modify the canopy architecture, and in turn, may affect the growth and yield of the crop (Taylor, 1975). Hunter (1980) concluded that a larger leaf area per plant of maize produced more assimilate in the plant, resulting in increased yield. Leach and Beach (1988) found that the larger canopy had greater water use efficiency, which was probably associated with a denser root system. Appropriate characteristics such as leaf arrangement, leaf shape and size, leaf angle and petiole length, may allow greater light penetration into the canopy, increasing photosynthetic activity in the middle and lower portion of the canopy (Board et al., 1992a). Duncan (1969) showed that erect leaf orientation is advantageous for the interception of solar radiation, minimizing mutual shading at high plant population. Erect leaf angles may allow more light to illuminate a greater leaf area and thus possibly increase seed yield. Light entering a canopy of erect leaves was spread over a large photosynthetic area compared to prostrate cultivars, resulting in greater photosynthetic efficiency. Hughes et al. (1987) found that an erectophile canopy of chickpea, had a significantly higher light interception over the growing season than a planophile canopy in northern Syria. They also reported that the normal plant population density (30 plants m^{-2}) appropriate for a planophile canopy, was inadequate for an erectophile canopy. This indicated that the best density suited to different crop architecture vary when water supply was variable and sporadic. Understanding the characteristics of canopy development material and light interception is important for chickpea breeders to identify genetic material with

ideal leaf types for the development of superior cultivars under optimum management practices for an environment.

2.5.4 Early season growth and development

In the following sections, the term "assimilate" is used to encompass both nitrogenous and photosynthetic compounds (N and C), while the term "photosynthate" will be used for the products of photosynthesis. Early in vegetative growth, photosynthates are directed towards canopy establishment, roots and nodule development (Tuner et al., 2005). In a short-growing season, any strategy that increases the rate of canopy closure, in order to increase canopy light interception early in the life cycle, should increase yield. One way to escape a probable end-of-season frost is to develop a cultivar with early growth vigor. Johansen et al. (1997) measured the relationship between chickpea early growth, shoot mass and harvested yield, in 123 chickpea genotypes grown in a Vertisol (deep clay soil) in India. He also found a linear positive relationship between early crop growth and seed yield. In a short-season Mediterranean-type environment, adaptation of kabuli chickpea requires increased early growth for rapid leaf cover and tolerance to low temperatures (Thomson and Siddique, 1999). Slow vegetative growth provided conditions for soil surface evaporation and a lower subsequent water use efficiency (Siddique and Sedgley, 1986; Leach and Beech, 1988). Penalties associated with earliness may include short-time biomass accumulation and a shallower root system (Kumar and Abbo, 2001).

2.5.5 Middle season growth and development

In chickpea, nitrogen fixation peaks between flower bud initiation and maximum flowering, then declines during pod filling so that by the time of early seed filling, 80% of the total nitrogen has been fixed (Hooda et al., 1986; Kurdali, 1996). Flowering time is important because environmental conditions during the reproductive phase have a major impact on final yield (Anwar et al., 2003b). Early flowering and early pod set should be a strategy for avoiding end-of-season frost. Especially in indeterminate chickpea, early flowering may enable the plants to prolong the reproductive phase, when the reproductive duration is limited by terminal frost. Penalties associated with early flowering include a shortened time for biomass accumulation and a shallower root system (Kumar and Abbo, 2001). A series of experiments conducted in Israel with standard late-flowering and early-flowering chickpea genotypes, showed that early-flowering types produced less biomass than late-flowering ones, however, the yield was similar. This study showed the best yield of desi chickpea was achieved by restricting vegetative growth, having an early onset of flowering and podding in a semiarid environment with less than 250 mm water availability for crop growth (Kumar and Abbo, 2001).

2.5.6 Late season growth and development

The major source of carbohydrates for the developing seed was thought to be the subtending leaf (Singh and Pandey, 1980). These researches found that 41% - 64% of the carbon produced by the subtending leaves of chickpea was transported to the associated pod. However, removal of the subtending leaf to a particular pod had

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no significant yield reduction, which indicated that other assimilates further away can compensate for the loss of the subtending leaves (Sheoran et al., 1987).

During reproductive development, production of vegetative tissue can be in direct competition with developing seeds in indeterminate chickpea (Khanna-Chopra and Sinha, 1987). The upper leaves, which bear flowers and pods in their axes were more important for seed filling than lower leaves, which do not possess flowers or pods (Turner et al., 2005). Singh and Pandey (1980) found that defoliation of upper leaves during reproductive stages decreased assimilate availability by 68%, while removal of lower leaves reduced assimilate by 30%. At the end of chickpea growth, leaf senescence was linked to pod development. The removal of pods and the failure of pod setting delayed leaf senescence (Saxena, 1984). In an environment prone to terminal drought, application of exogenous nitrogen at flowering increased the nitrogen available for seed filling, biomass production, yield and seed protein of chickpea (Palta et al., 2005). In field-grown chickpea, both the maximum seed growth rate and duration of seed growth were reduced under terminal drought (Turner et al., 2005)

For chickpea and specifically kabuli chickpea, there is little information regarding the relationship of the two leaf types and their performance in growth and yield partitioning and specifically, which leaf type may be best suited for western Canada.

3.0 Performance of kabuli chickpea cultivars with the fern or unifoliate trait

3.1 Introduction

The method a plant canopy uses to intercept radiation is a crucial factor in determining canopy photosynthesis and crop yield, especially in the Northern Great Plains where limited solar radiation is available during the growing season. The ideal chickpea cultivar for a short season should have rapid initial leaf area development for high light interception, leading to rapid early season plant growth and, therefore, high yield. In kabuli chickpea, there are several leaf types, two of which are the fern leaf and unifoliate leaf with different leaf shape and size, controlled by a single gene (Muehlbauer and Singh, 1987). Besides the fern leaf and unifoliate leaf, three additional leaf types are narrow leaflets, tiny leaflets and bipinnate leaf. A canopy with the best leaf arrangements that maximize light interception and optimize radiation use efficiency could further improve yield.

Evaluation of canopy architecture and morphology as selection criteria for chickpea might increase yield. Leaf size in the upper canopy may affect yield response to plant population. Larger leaf size causing canopy closure were reported by Wells et al. (1993) and Heitholt et al. (2005) in soybean. Soltani et al. (2006) quantified the effects of temperature, photoperiod and plant population on plant leaf area in chickpea and developed a two-phase segmental model for leaf production

per plant: Phase 1 when plant leaf number increases at a lower rate and Phase 2 with a higher rate of leaf production per plant. They found that plant populations ranging from 15, 30, 45 and 60 plants m^{-2} did not affect rate of leaf production in Phase 1. However, in Phase 2, rate of leaf production decreased with increases in plant population up to 41 plants m^{-2} and then stabilized. Plant population did not affect leaf size. However, there was a highly significant relationship between plant leaf area with plant population. Siddique et al. (1984) suggested that leaf number was more important compared to leaf size in controlling LAI, and hence the rate of canopy closure and early water use by chickpea. Duncan (1969) showed that erect leaf orientation is advantageous for the interception of solar radiation, minimizing mutual shading at high plant population. Whether fern leaf differs with unifoliate leaf in leaf orientation is still unknown.

Increasing plant population is one management tool for increasing the capture of solar radiation within the canopy. Duncan (1986) postulated that seed yield increases were possible at plant populations higher than required for near complete light interception. Siddique et al. (1984) proposed a higher yielding chickpea ideotype for short-season environment should have no more than two branches at high population. Chickpea at low population densities did not compensate by producing more branches, and branch appearance in order was faster in lower population densities compared with high population densities. Researchers found that yield increased at plant populations above those required for nearly complete light interception in indeterminate cultivars (Shibles and Weber, 1966, Egli, 1988). Siddique et al. (1984) also reported that higher plant population had a

faster initial LAI development in chickpea. However, high population densities also caused greater soil water extraction during the flower growth and lower harvest index in pea (Martin et al., 1994).

Difference in crop morphology and how crop morphology affects the response to plant population is often a concern in soybean and cotton (Heitholt et al., 1992; Heitholt, 1994; Heitholt et al., 2005). In this study, I hypothesized that each leaf type (fern or unifoliate leaf) could contribute to differences in seed yield by HI, biomass accumulation, CGR. Genotypes differing in leaf type may also respond differently to plant population. I also hypothesize that fern leaf cultivars have greater leaf area, more rapid canopy closure, and higher light interception than the unifoliate cultivars. Moreover, when seeded at higher plant populations than recommended, fern leaf cultivars would increase season-long light interception and result in higher yield potential. The objectives of this research were (1) to determine the relationship between leaf type and crop growth rate, maximum above-ground biomass, maximum light interception, radiation use efficiency, HI and yield under moderate and high plant population densities, and (2) to assess the best leaf type for optimal crop growth and yield in semi-arid short season production.

3.2 Materials and Methods

3.2.1 Site and plot information

Field experiments were conducted in 2003 and 2004 at Goodale Experiment Farm at Saskatoon (52.1' N, 106.41' W) on a Dark Brown Chernozem soil (Typic Borolls), and at the Agriculture and Agri-Food Canada Research Center, Swift Current (50.2' N, 107.4' W) on an Orthic Brown Chernozem (Aridic Haploborolls).

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At Saskatoon in 2003, each plot consisted of 6 rows 4.9 m long with 0.3 m row spacing, and in 2004 plot length and row spacing were the same with 16 rows per plot. At Swift Current, plots were six rows wide with 0.3 m row spacing and 6.7 m row length in 2003 and 10 m row length in 2004. Minimum and maximum air temperature, rainfall and incident total solar radiation were recorded on an automatic weather station near the plots at Saskatoon and a standard meteorological station at Swift Current.

3.2.2 Experimental design

Six kabuli chickpea cultivars commonly grown in the Northern Great Plains were used in this study. Three cultivars had fern leaf type (cv. Amit, CDC ChiChi, and CDC Yuma) and three cultivars had unifoliate leaf type (cv. CDC Xena, Evans, and Sanford). The cultivars were grown at moderate (45 plants m^{-2}) and high (85 plants m^{-2}) plant population densities at each location-year. In each of the four location-years, the experiment was a randomized complete block design with four replicates and a factorial arrangement of treatments (six cultivars and two population densities).

Seed was sown at a depth of 50 mm on 14 May (2003) and 25 May (2004) on wheat stubble at Saskatoon, and on 20 May (2003) and 14 May (2004) on conventional summerfallow at Swift Current. Plots received 5.5 kg ha^{-1} of commercial granular rhizobia inoculant (Becker Underwood, Saskatoon, SK) for symbiotic N fixation at seeding. At Saskatoon in 2003, weeds were managed with ethalfluralin (Granular Edge) at a rate of 28 kg ha^{-1} applied in the spring before seeding. Pre-emergence herbicide imazethapyr (Pursuit) at a rate of 0.07 L ha^{-1} was

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applied for weed control. The fungicides chlorothalonil (Bravo) at a rate of 3.2 L ha^{-1} and pyraclostrobin (Headline) at a rate of 0.4 L ha^{-1} were applied to control fungal disease ascochyta blight. Bravo was used when chickpea plants began flowering, and Headline was used twice at 10 d intervals. In 2004, weeds at Saskatoon were controlled using a pre-seeding application of ethalfluralin (Granular Edge) plus a pre-emergence application of imazethapyr. Application of chlorothalonil was used at initial flowering, followed two sprays separated by 10 d intervals of pyraclostrobin at the same rate used in 2003. At Swift Current in 2003, weeds were controlled using a pre-seeding application of ethalfluralin at a rate of 17 kg ha^{-1} on 8 May, a pre-emergence application of glyphosate (Roundup) at a rate of 2.5 L ha^{-1}, and imazethapyr (Pursuit) at a rate of 0.03 L ha^{-1} on 21 May, and a post-emergence application of sethoxydim (Poast Ultra) at a rate of 0.48 L ha^{-1} on 17 June. Four applications of fungicide were used in 2003 to control ascochyta blight, including pyraclostrobin (Headline) at 0.40 L ha^{-1} on 27 June and 11 July, chlorothalonil (Bravo) with the rates of 4.0 L ha^{-1} on 18 June and 3.0 L ha^{-1} on 24 July at Swift Current in 2003.

In 2004, weeds at Swift Current were managed with a pre-seeding application of ethalfluralin on 26 April with supplemental pre-emergence application of glyphosate (Roundup) at a rate of 0.88 L ha^{-1} and imazethapyr (Pursuit) at a rate of 0.03 L ha^{-1} on 20 May, as well as a post-emergence application metribuzin (Sencor) at a rate of 0.30 L ha^{-1} on 9 June.

Grasshoppers were controlled in 2003 at both Saskatoon and Swift Current. Chlorpyrifos (Lorsban) was sprayed twice at a rate of 1L ha^{-1} during reproductive

growth (early flowering and mid pod fill) at Saskatoon, and dimethoate (Cygon) was sprayed at first flower at a rate of 0.5 L ha^{-1}.

3.2.3 Measurements and calculations

Stand establishment was assessed four to five weeks after seeding by counting 1 m length of a row at two positions in each plot, which represented two 0.30 m^2 areas. Beginning at approximately the fourth-node stage until plant physiological maturity, above-ground biomass was sampled from the center four adjacent 0.25-m-long rows (0.30 m^2) per plot. Samples were dried at 60 $^{\circ}$C for 6 to 7 d and weighed. Crop growth rate was calculated by regressing biomass (dependent variable) against time (independent variable) in the linear portion of growth. Crop growth was approximately linear between 35 days after emergence (DAE) and 62 DAE at Saskatoon 2003, 26 and 70 DAE at Saskatoon 2004, 28 and 62 DAE at Swift Current 2003 and 35 and 86 DAE at Swift Current 2004.

Light interception was determined in the same day as biomass sampling at approximately 10 d intervals using a 1-m-long line quantum sensor (Model LI-191SA, Licor, Lincoln, NE). Measurements were made between 1000 and 1430 h on days when light intensity was greater than 1500 μmol photo m^{-2} s^{-1}, in unobstructed light. Three measurements below the canopy near the soil surface where the line quantum sensor was placed perpendicular to the row with one measurement above the crop canopy. To calculate light interception for a given day and plot, I assume that the diffuse component increases linearly with respect to the measured values. Light interception was calculated as

Light interception= 1-[(average PAR below canopy) (PAR above canopy)$^{-1}$]   [1]

Photosynthetically active radiation (PAR) was calculated as one-half of the total solar radiation (Monteith, 1972). Canopy light interception ($MJ\ m^{-2}\ d^{-1}$) for each day of a given plot was calculated by multiplying predicted fractional light interception by daily total PAR. Intercepted PAR was cumulated for each plot from emergence to physiological maturity. Radiation use efficiency was obtained as the slope of regression between cumulative biomass and cumulative intercepted radiation.

At pod filling stage, a plant was randomly selected from each plot, all the fully expanded leaves from both the main stems and branches were harvested. Leaf blade area was determined with a Li-Cor Model 3100 Leaf Area Meter (Li-Cor, Inc., Lincoln, NE). When chickpea cultivars reached harvest maturity, plots were harvested using a plot combine. At Saskatoon, the harvest area of each plot was 10 m^2 in 2003 and 21 m^2 in 2004. At Swift Current, 10 m^2 in 2003 and 16 m^2 in 2004 were harvested. Harvested seeds were dried at 60 ^{o}C for a week, cleaned and weighed for seed yield.

3.2.4 Data analysis

Data were analyzed using analysis of variance in the general linear model procedure (PROC GLM) of SAS (Version 8.2, SAS Inst., 1999) for each location-year with block, cultivar and population as fixed effects. Means were separated by Fisher's protected Least Significant Difference (LSD) test at $P \leq 0.05$. A single degree of freedom contrast was used to determine the difference between fern and unifoliate leaf types in plant population, maximum biomass, CGR, maximum light interception, cumulative intercepted radiation, RUE, harvest index and seed yield.

3.3 Results

3.3.1 Growing season environment

The 2003 growing season in Saskatoon was characterized by above normal mean air temperature in May (Table 3.1), followed by normal mean temperature in June, July and ended with higher air temperature in August. Similar weather patterns occurred at Swift Current, except that air temperatures were above normal in both July and August. Rainfall at both locations in 2003 was below normal throughout the growing season, except in July for Saskatoon and June for Swift Current. Year 2003 was considered a severe drought year, with crops limited predominantly by lack of rain. High temperatures coupled with a low rainfall in 2003 produced low kabuli chickpea yields at both Saskatoon (893 kg ha^{-1}) and Swift Current (804 kg ha^{-1}).

In 2004, air temperatures were below normal during the whole growing season except in September, while total precipitation was 25% (Saskatoon) to 30% (Swift Current) higher than normal. Cool temperatures, higher than normal rainfall and a longer growing season made 2004 a more favorable year for chickpea production compared to 2003 with mean seed yields being 1135 kg ha^{-1} at Saskatoon and 2468 kg ha^{-1} at Swift Current.

3.3.2 Chickpea establishment

Spring weather conditions were adequate for stand establishment at Saskatoon and Swift Current in 2004 (Table 3.2). However, plant population densities were lower than the targets in 2003, especially at Swift Current in 2003 where no rain fell for 10 d following seeding and herbicide damage (Granular Edge)

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Table 3.1 Summary of meteorological conditions during the experiments at Saskatoon and Swift Current in 2003 and 2004.

Month	Saskatoon			Swift Current		
	2003	2004	30-year average [†]	2003	2004	30-year average [a]
			Maximum temperature (^{o}C)			
May	19.9	14.7	18.4	17.2	13.9	17.9
June	23.1	18.9	22.6	21.1	18.8	22.2
July	25.7	22.8	24.9	27.8	23.8	24.9
August	28.4	20.1	24.4	28.9	21.2	24.6
September	17.7	18.2	18.0	17.7	18.6	18.1
			Minimum temperature (^{o}C)			
May	3.6	1.1	4.5	4.7	2.7	4.2
June	8.7	7.1	9.4	9.2	7.3	8.7
July	10.6	11.1	11.4	11.8	11.8	10.8
August	12.7	7.7	10.2	14.0	9.4	10.1
September	4.8	5.8	4.4	5.9	6.1	4.6
			Mean air temperature (^{o}C)			
May	11.8	7.9	11.5	11.0	8.3	11.0
June	15.9	13.0	16.0	15.1	13.0	15.5
July	18.2	18.3	18.2	19.8	17.8	17.9
August	20.6	15.1	17.3	21.5	15.3	17.4
September	11.3	11.8	11.2	11.8	12.3	11.4
			Rainfall (mm)			
May	13.8	36.0	46.8	41.9	83.7	45.3
June	30.8	86.6	61.1	78.7	66.2	67.9
July	63.9	74.8	60.1	8.3	61.1	55.2
August	31.4	73.0	38.8	20.7	72.3	43.5
September	38.7	24.5	29.0	39.0	27.4	26.6
Total	178.6	294.9	235.8	188.6	310.7	238.5

[†] from 1974 to 2003

Table 3.2 Stand establishment at early vegetative growth for kabuli chickpea cultivars at Saskatoon and Swift Current in 2003 and 2004.

Cultivar and leaf type	Target plant density (Plants m^{-2})	Achieved plant density (Plants m^{-2})			
		2003		2004	
		Saskatoon	Swift Current	Saskatoon	Swift Current
Fern leaf					
Amit	45	39	17	47	39
	85	66	30	64	59
CDC ChiChi	45	32	17	45	43
	85	63	20	70	59
CDC Yuma	45	37	14	46	34
	85	59	30	61	60
Unifoliate leaf					
Evans	45	40	16	48	31
	85	67	27	67	43
Sanford	45	45	19	45	34
	85	62	27	66	53
CDC Xena	45	40	20	41	45
	85	74	24	65	66
LSD (0.05)[‡]		12	5	13	11
45 plants m^{-2}		39	17	45	38
85 plants m^{-2}		65	26	66	57
Contrast for population		**	**	**	**
Fern leaf		49	21	55	49
Unifoliate leaf		52	22	55	45
Contrast for leaf type		*	NS	NS	NS

*, ** indicates statistical significance at P≤0.05 and P≤0.01 levels, respectively.
NS indicates no significant difference at P≤0.05.
[‡] LSD compares means between cultivars at each location year.

effect. Leaf type and plant population interactions for stand establishment were not significant in four location-years (Appendix 1). Plant population density did not differ between two leaf types except at Saskatoon 2003, when the unifoliate cultivars had a higher crop establishment than the fern leaf cultivars (Table 3.2). The plant population at all four location-years differed significantly amongst each other.

3.3.3 Phenological development

The rate of seedling emergence was faster in 2003 compared to 2004 at both locations due to the higher mean air temperatures in May 2003 (Table 3.3). The low temperature and rainfall also postponed the time of first flower in 2004, but had no effect on the duration of vegetative growth between emergence and first flowering. Reproductive growth duration extended 65 days in Saskatoon 2004 and 42 days in Swift Current 2004 compared to the 2003 locations. Crop duration in 2004 was almost two months longer than in 2003 because chickpea is indeterminate and the high rainfall and cool temperatures in 2004 extended growth and delayed maturity.

3.3.4 Dry matter production, maximum biomass and crop growth rate

To illustrate dry matter response, I chose the least productive and most productive location by year combinations for discussion (Saskatoon 2003 and Swift Current 2004, respectively). Above-ground biomass exhibited a linear increase in all cultivars at Saskatoon 2003 (Figure 3.1). A similar pattern was seen when based on time only. The pattern of dry matter production was linear during the early and middle of the growing season at Swift Current 2004; the nonlinear dry matter production towards the end of the growing season was caused by excessive rainfall,

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Table 3.3 Phenological development as days after sowing for kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Year	Location	Seeding date	Emergence	First Flowering	Physiological maturity
2003	Saskatoon	14 May	9	47	86
	Swift Current	20 May	9	46	83
2004	Saskatoon	25 May	17	55	159
	Swift Current	14 May	19	60	139
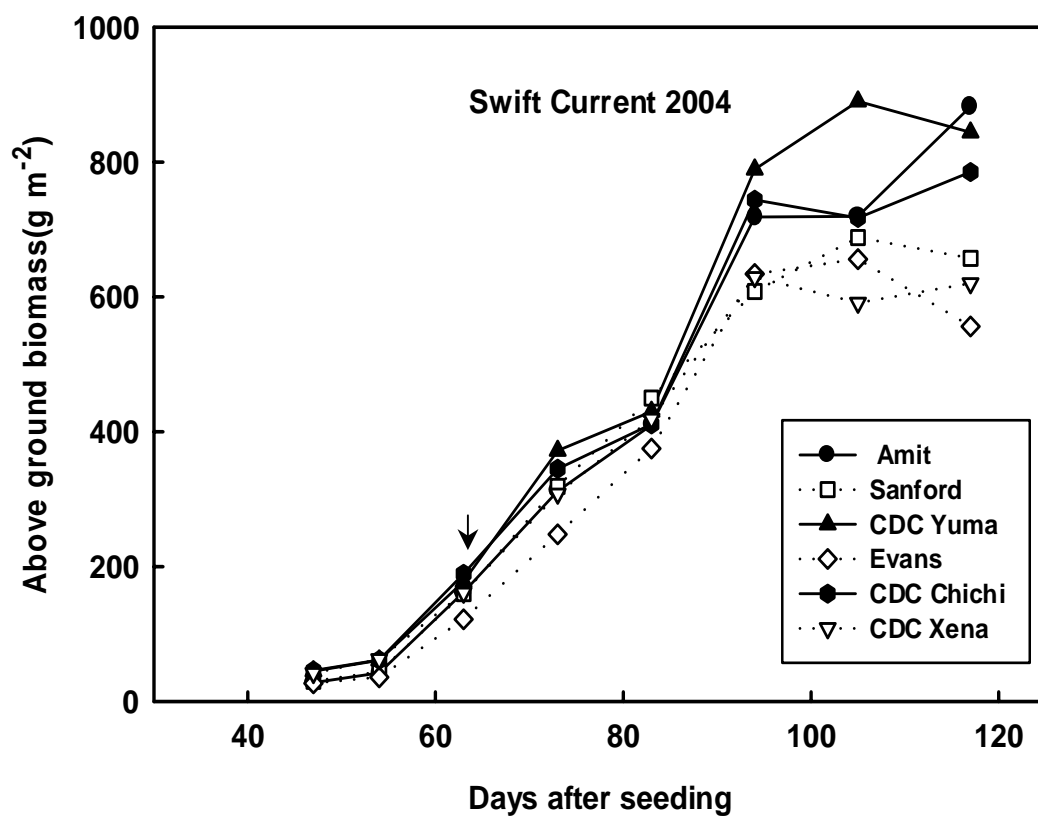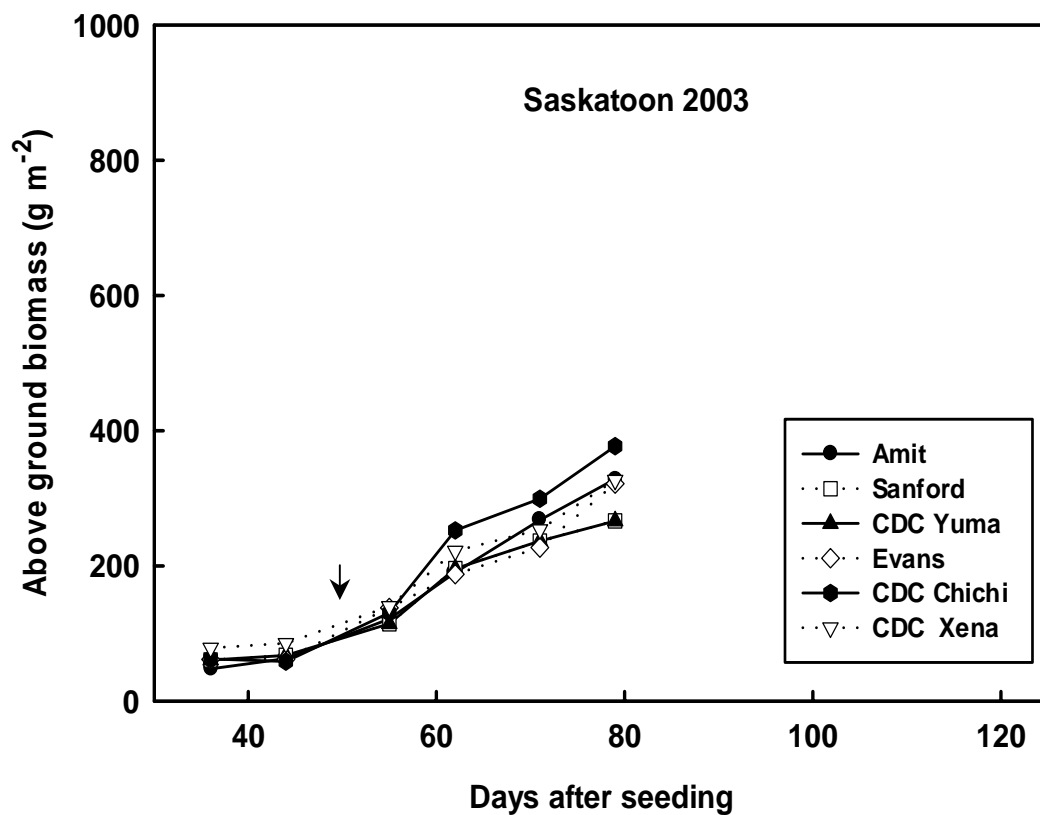
Figure 3.1 Above-ground biomass of six kabuli chickpea cultivars in Saskatoon 2003 and Swift Current 2004. The arrow indicates the time of flowering.

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the indeterminate growing habit of chickpea, and differences in crop

maturity(Figure 3.1). Chickpea cultivars produced more than twice the dry matter

in 2004 compared to both 2003 locations; 2003 growth was limited by drought.

Leaf type and plant population interactions for dry matter production at most

of sampling dates were not significant at Saskatoon in 2003 (Appendix 2) and Swift

Current in 2004(Appendix 3). Interestingly, the unifoliate leaf cultivars produced

more dry matter during the early growing season, even after flowering in the dry

conditions at Saskatoon in 2003 (Figure 3.2). In contrast, the fern leaf cultivars

accumulated more dry matter than the unifoliate leaf during the whole growing

season at Swift Current in 2004, except during three weeks in the middle of growing

season when temperatures were cool and precipitation was high (Figure 3. 2). The

fern leaf types at both locations had a higher crop growth rate in two location-years

(bottom of Table 3.4). Stand establishment was similar for both leaf types at Swift

Current 2004, but the fern leaf exhibited higher light interception (maximum light

interception for the fern and unifoliate leaf types leaf were 91% and 78%,

respectively) and a higher CGR at two out of four location-years (Table 3.4),

resulting in greater biomass.

Leaf type and plant population interactions for maximum above-ground

biomass were not significant in four location-years (Appendix 4). In 2004, chickpea

cultivars produced almost twice the maximum above-ground biomass than 2003 at

both locations. There was no difference between the leaf types for the maximum

above-ground biomass (Table 3.4). However, the treatment of 85 plants m^{-2}

accumulated greater maximum biomass than 45 plants m^{-2} at Saskatoon for both
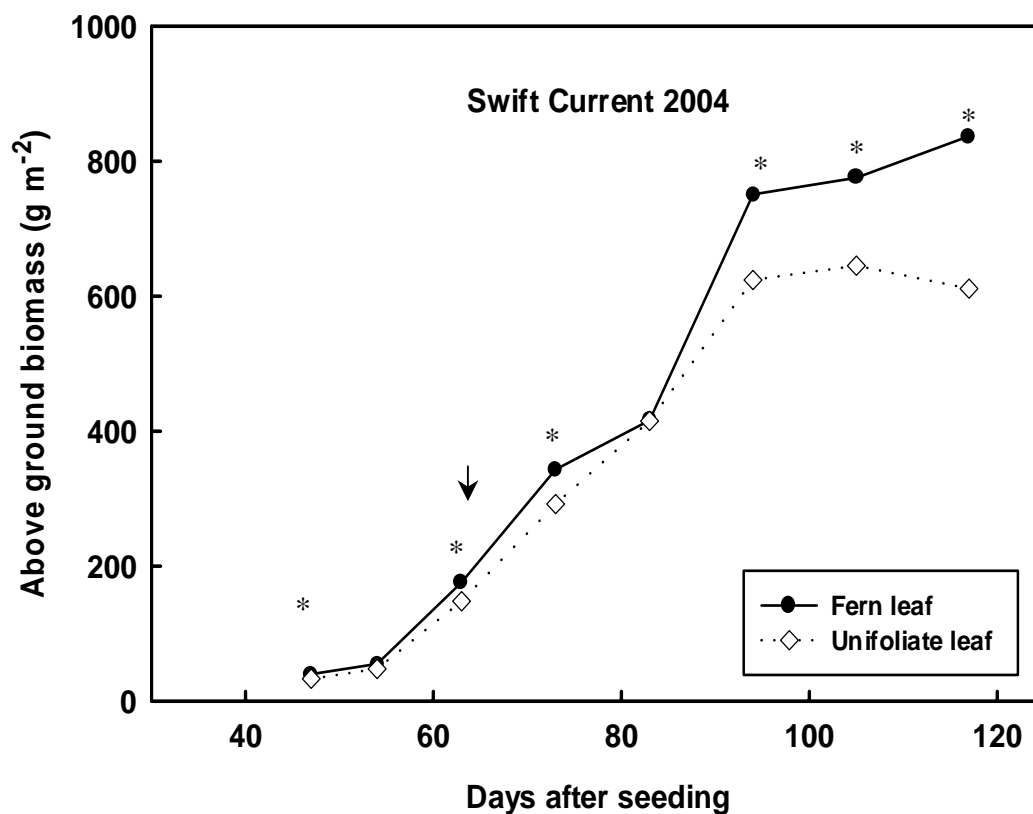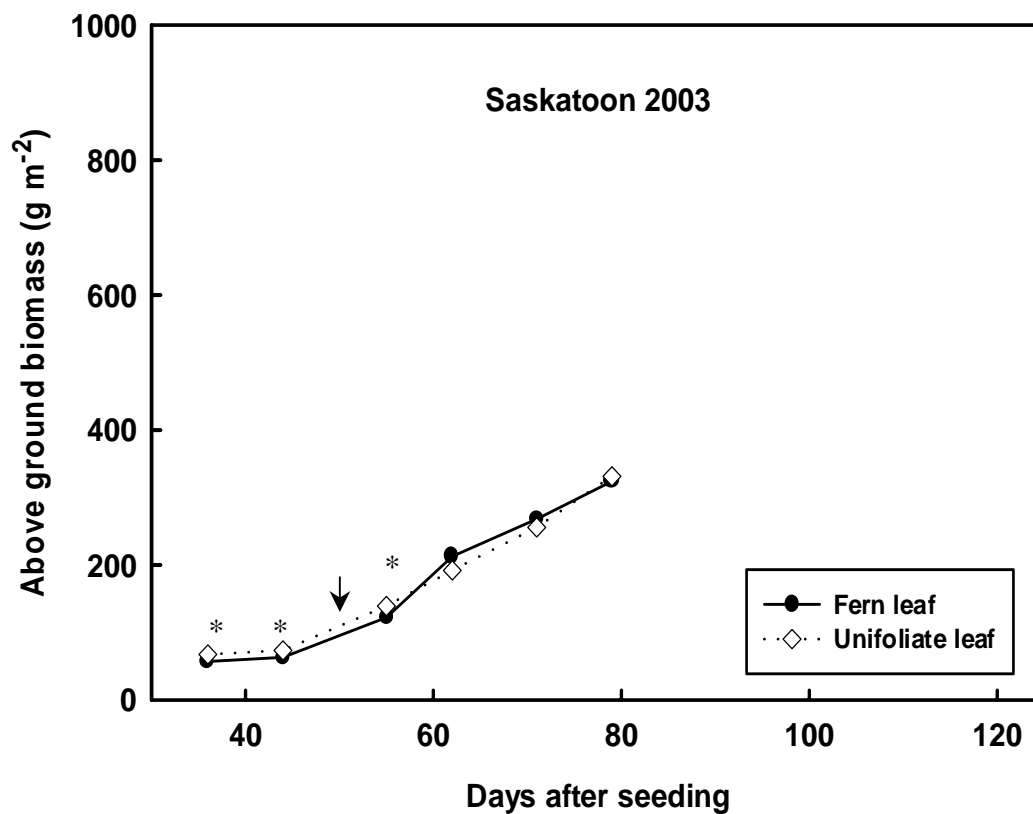
Figure 3.2 Above-ground biomass of fern and unifoliate-leaf chickpea cultivars in Saskatoon 2003 and Swift Current 2004. The arrow indicates the time of flowering, and * indicates biomass differed significantly at P<0.05 between the fern and unifoliate leaf types.

Table 3.4 Effect of leaf type and population on maximum above ground biomass and crop growth rate of chickpea at Saskatoon and Swift Current in 2003 and 2004.

Cultivar and leaf type	Maximum above ground biomass ($g\ m^{-2}$)				Crop growth rate ($g\ m^{-2}\ d^{-1}$)			
	Saskatoon		Swift Current		Saskatoon		Swift Current	
	2003	2004	2003	2004	2003	2004	2003	2004
Fern leaf								
Amit	342	617	323	921	7.7	10.3	7.4	14.4
CDC ChiChi	380	650	318	853	10.8	10.5	7.3	14.0
CDC Yuma	278	586	299	930	6.6	11.0	7.5	16.9
Unifoliate leaf								
Evans	322	597	312	742	7.1	10.9	8.2	13.3
Sanford	352	637	308	766	7.6	10.7	7.0	13.1
CDC Xena	327	624	324	722	6.6	11.5	7.8	11.6
LSD (0.05)[‡]	25	NS	46	114	1.8	NS	NS	2.4
45 plants m^{-2}	321	589	296	824	7.9	10.4	7.5	14.2
85 plants m^{-2}	346	649	332	820	7.5	11.2	7.6	13.5
Contrast for population	*	*	*	NS	NS	NS	NS	NS
Fern leaf	333	618	313	901	8.4	10.6	7.4	15.1
Unifoliate leaf	333	620	315	743	7.1	11.0	7.7	12.7
Contrast for leaf type	NS	NS	NS	**	*	NS	NS	*

*, ** indicates statistical significance at P≤0.05 and P≤0.01, respectively.
NS indicates no significant difference at P≤0.05.
[‡]LSD compares means between cultivars at each location year.

years and at Swift Current in 2003 as expected. The reason for similar maximum

biomass at 45 plants m^{-2} and 85 plants m^{-2} at Swift Current in 2004 is not

understood. Seasonal CGR were highly associated with maximum biomass.

In the wet year of 2004, all cultivars exhibited almost 150% of the CGR of

the dry year of 2003 except CDC ChiChi, which is probably due to CDC ChiChi

being more drought tolerant than the others (Table 3.4). Leaf type and plant

population interactions for crop growth rate were not significant in four location-

years (Appendix 5). Crop growth rate was not significantly affected by plant

population (Table 3.4). The chickpea cultivars with fern-leaf trait exhibited a higher

crop growth rate at Saskatoon (2003) and Swift Current (2004), indicating the fern

leaf had superior canopy assimilation than the unifoliate leaf.

3.3.5 Effects of plant population and leaf type on light interception and maximum light interception

Light interception patterns during the 2003 and 2004 growing season were

different (Figure 3.3). In 2003, the chickpea cultivars took less time to reach

maximum light interception at both locations compared to 2004. The light

interception development patterns in 2003 were similar to those reported by Thomas

and Fukai (1995) with a slow early leaf expansion until a peak was reached,

followed by a decline during the later growth period. In 2004 at both locations,

canopy light interception declined between 50 and 60 days and then increased again,

which was caused by temporary leaf wilting and rolling due to drought followed by

regrowth due to rain. Light interception was less in 2003 compared to 2004 (Figure

3.3). There are four possible explanations (1) higher mean temperature in 2003

compared to the cooler and high rainfall conditions prevalent in 2004; (2) limitation

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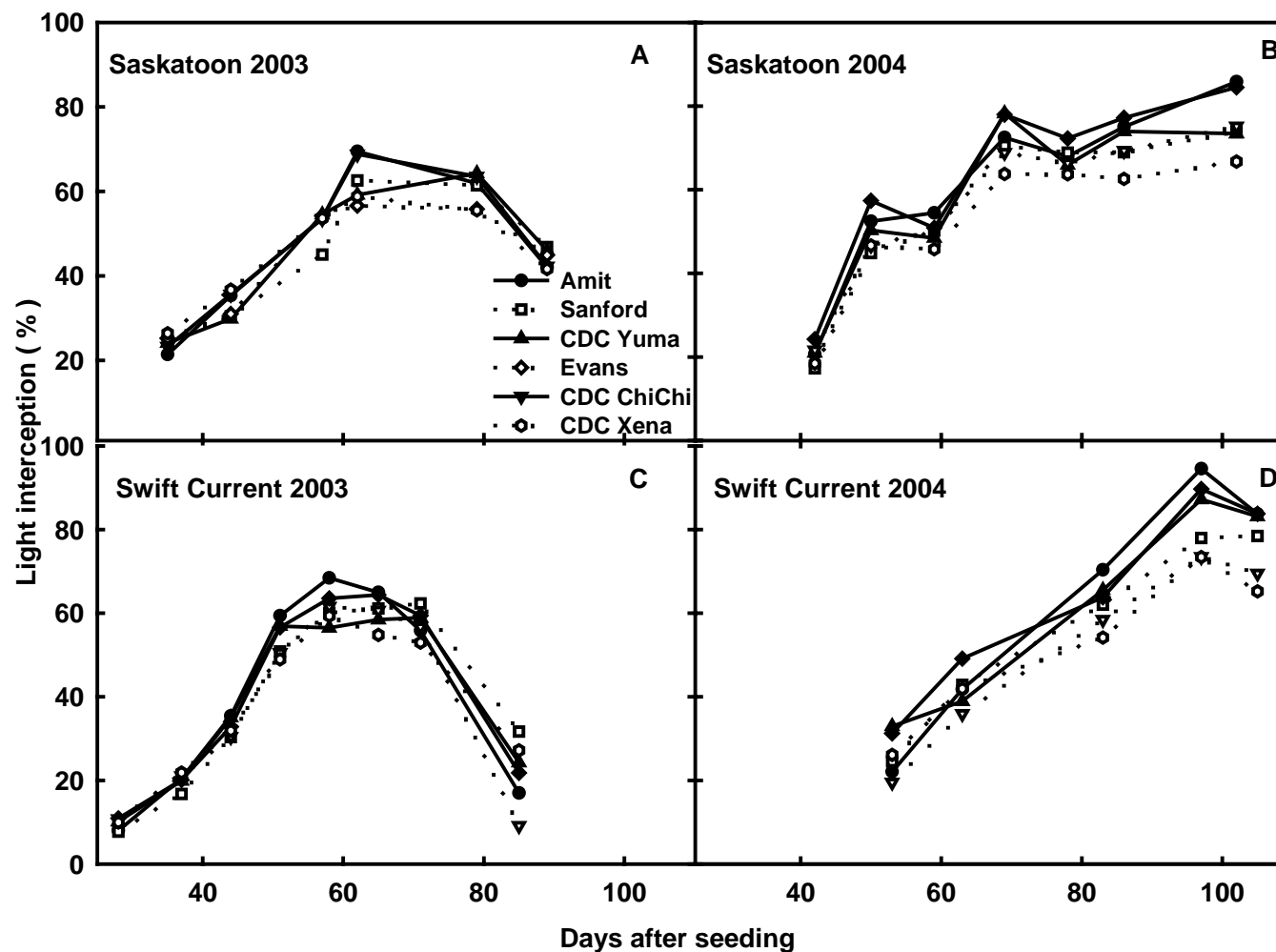
Figure 3.3 Light interception of kabuli chickpea canopy as a function of days after seeding in four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively.

of leaf area expansion induced by drought; (3) temporary leaf wilting during the period of drought; and (4) early leaf senescence caused by water stress (Hughes et al., 1987).

Leaf type and plant population interactions for maximum light interception were not significant in four location-years (Appendix 6). For the four location-years the maximum light interception value achieved in a season (Table 3.5) ranged from 60% to 95%. In 2003, maximum light interception ranged from 60 to 71% and 60 to 72% in Saskatoon and Swift Current, respectively. In 2004, maximum light interception varied from 72 to 85% and 74 to 95% for Saskatoon and Swift Current, respectively. Thus none of the canopies achieved the optimum leaf area for achieving 95% light interception. Optimal light interception of 95% did not occur in the dry year 2003. The greatest maximum light interception values were from the fern-leaf cultivars Amit and CDC ChiChi, and fern leaf cultivars had a higher maximum light interception at all four location-years. Fern leaf cultivars intercepted more light than unifoliate leaf cultivars during the middle of the growing season in 2003 (Figure 3.4A, 3.4C). At Swift Current (2004), by 53 DAS, the fern leaf exhibited a greater light interception than the unifoliate leaf regardless of plant population, and this advantage was observed throughout the season.

Leaf type and plant population interactions were not significant at all sampling dates in four location-years (Appendix 7). Only at Saskatoon 2003, I found an advantage for high populations, where maximum light interception was greater (Table 3.5). For the other three location years, plant population had no

Table 3.5 Effect of leaf type and plant population on maximum light interception and seasonal intercepted radiation at Saskatoon and Swift Current in 2003 and 2004.

Cultivar and leaf type	Maximum Light Interception				Seasonal Cumulative Intercepted Radiation			
	%				MJ m^{-2}			
	Saskatoon		Swift Current		Saskatoon		Swift Current	
	2003	2004	2003	2004	2003	2004	2003	2004
Fern leaf								
Amit	71	86	72	95	270	336	290	422
CDC ChiChi	69	88	68	91	285	357	286	463
CDC Yuma	67	81	62	88	194	326	278	454
Unifoliate leaf								
Evans	61	78	65	77	292	321	272	341
Sanford	67	76	66	82	263	321	276	392
CDC Xena	60	72	60	75	299	292	264	368
LSD (0.05) [†]	6	6	6	4	101	28	23	40
45 plants m^{-2}	64	79	65	84	265	313	263	380
85 plants m^{-2}	67	81	66	85	269	338	292	433
Contrast for population	*	NS	NS	NS	NS	*	**	**
Fern leaf	69	85	68	91	249	340	289	446
Unifoliate leaf	63	75	64	78	285	312	277	367
Contrast for leaf type	*	**	*	**	NS	*	*	**

*, ** indicate statistical significance at the 0.05 and 0.01 levels, respectively.

NS indicates no significant differences at P ≤ 0.05.

[†] LSD compares means between cultivars at each location year.
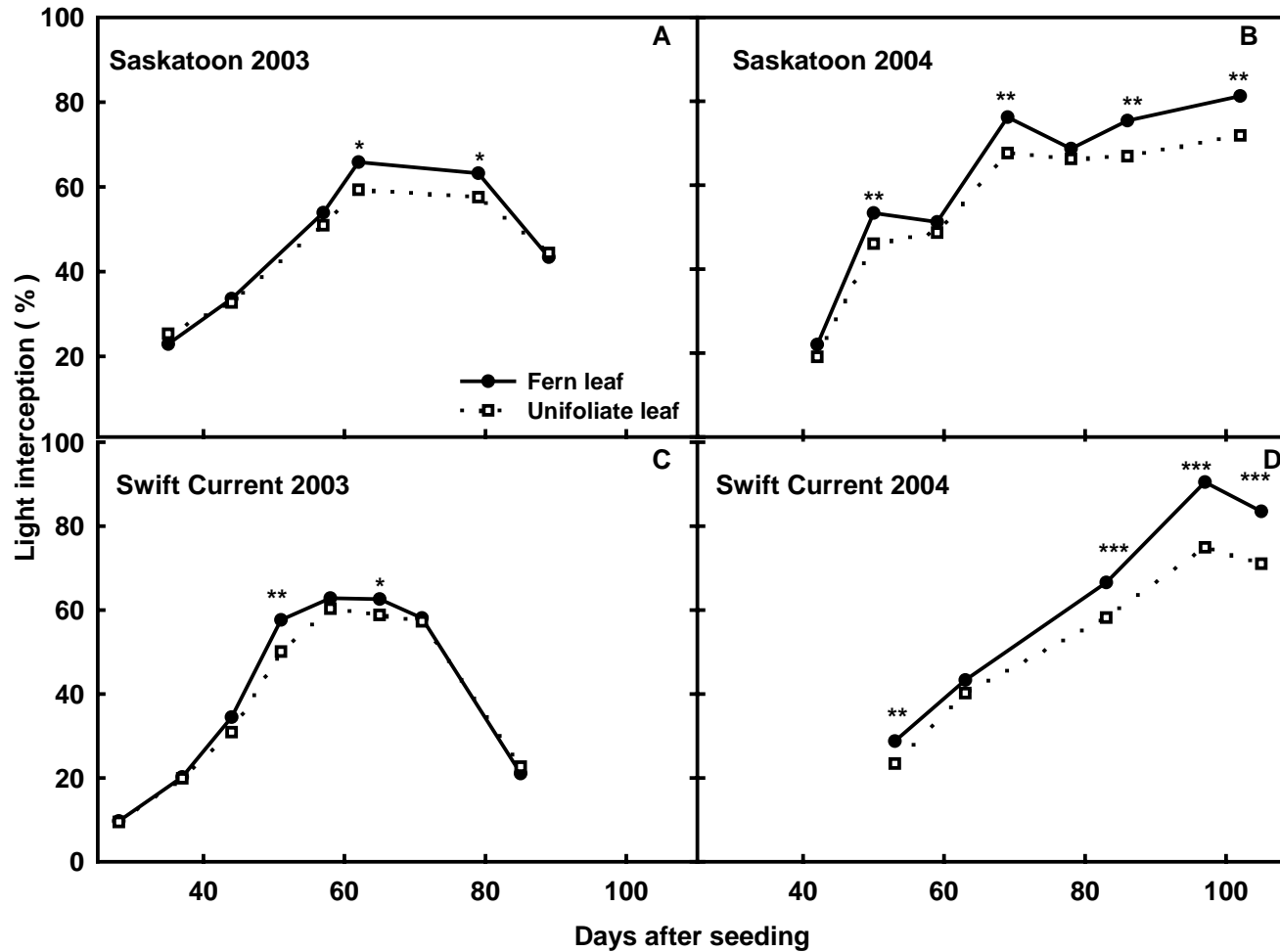
Figure 3.4 Light interception of fern-leaf and unifoliate-leaf canopy of kabuli chickpea as a function of time in four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively. *, **, *** indicate that light interception differed significantly within a day between two leaf types at the 0.05, 0.01 and 0.001 levels of probability, respectively.

effect on the maximum light interception. The high light interception values for the

fern-leaf cultivars can be attributed to erect canopy architecture, while the unifoliate

leaf has a relatively more planophile canopy structure. A fern leaf also has a larger

surface area (about 825 mm^2 compared to 514 mm^2 for a unifoliate leaf), which is

also consistent with the work of Singh (1991), where a decrease in leaf area index of

chickpea caused a reduction in light interception.

Light interception was lower at 45 plants m^{-2} than at 85 plants m^{-2} up to mid

season, but then this difference decreased as the growing season advanced for all the

four location-years (Figure 3.5). The difference between two densities disappeared

after flowering. During later growth period, the advantage of higher plant

population disappeared possibly due to limited resources. A similar trend was found

in desi chickpea, narrow-leafed lupin, lentil and field pea as intercepted radiation

increased with increasing plant population (400 plants m^{-2}), in a subhumid

temperate environment (Ayaz et al., 2004).

3.3.6 Effects of plant population and leaf type on cumulative intercepted radiation

The pattern of cumulative intercepted radiation development (Figure 3.6)

was similar in four location years. Leaf type and plant population interaction were

not significant for cumulative intercepted radiation at all the sampling dates at

Saskatoon in 2003 and Swift Current in both 2003 and 2004 (Appendix 9).

However, there were significant leaf type and plant population interaction at all the

sampling dates at Swift Current in 2004 (Appendix 9). Fern leaf had a greater

cumulative intercepted radiation than unifoliate leaf at the end of the growing

season at Saskatoon and exhibited greater cumulative intercepted radiation from

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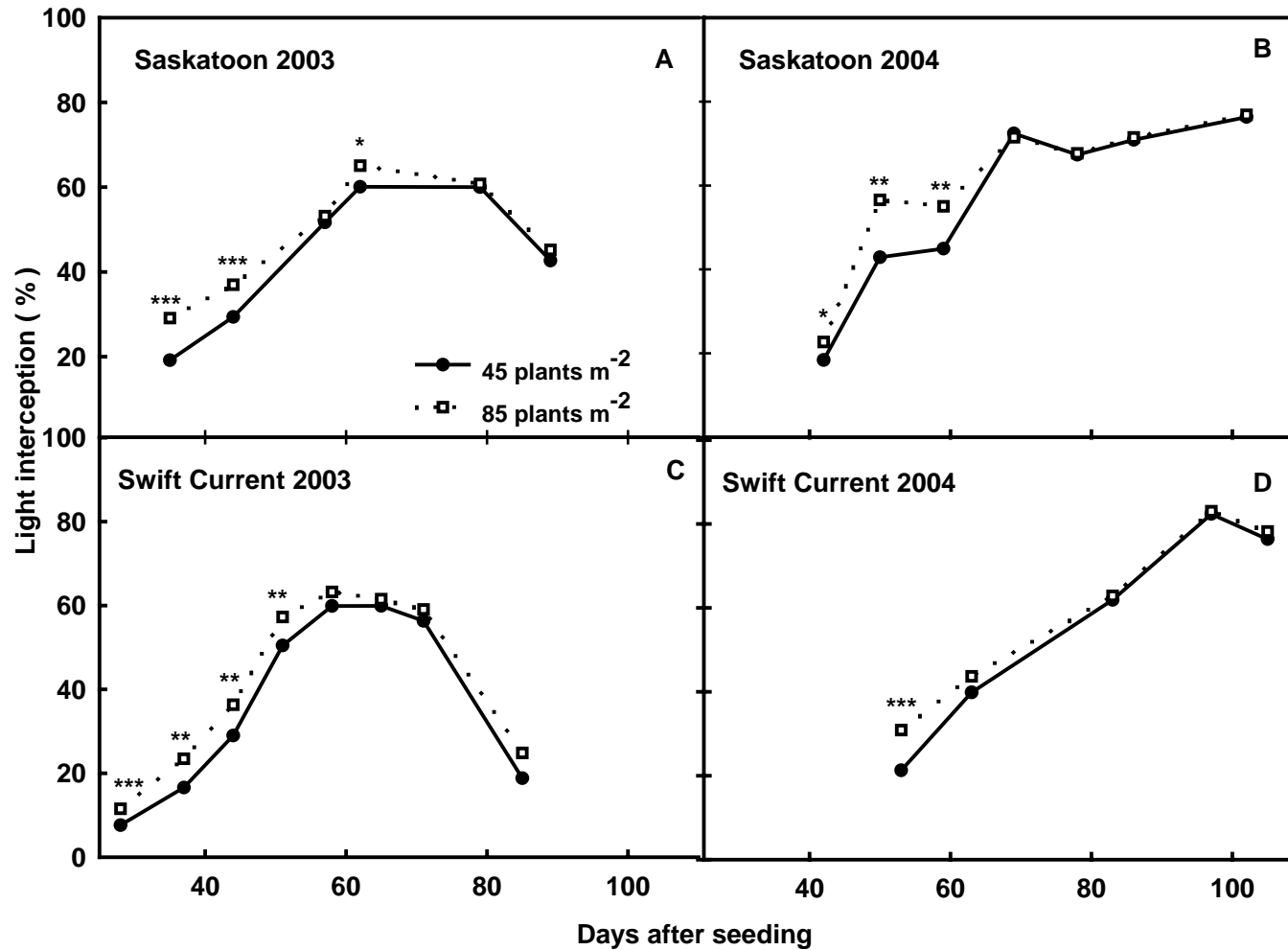
Figure 3.5 Light interception of kabuli chickpea canopy at two plant densities (45 plants m^{-2} and 85 plants m^{-2}) as a function of time at four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively. *, **, *** indicate that light interception differed significantly within a day between two plant densities at the 0.05, 0.01 and 0.001 levels of probability, respectively.
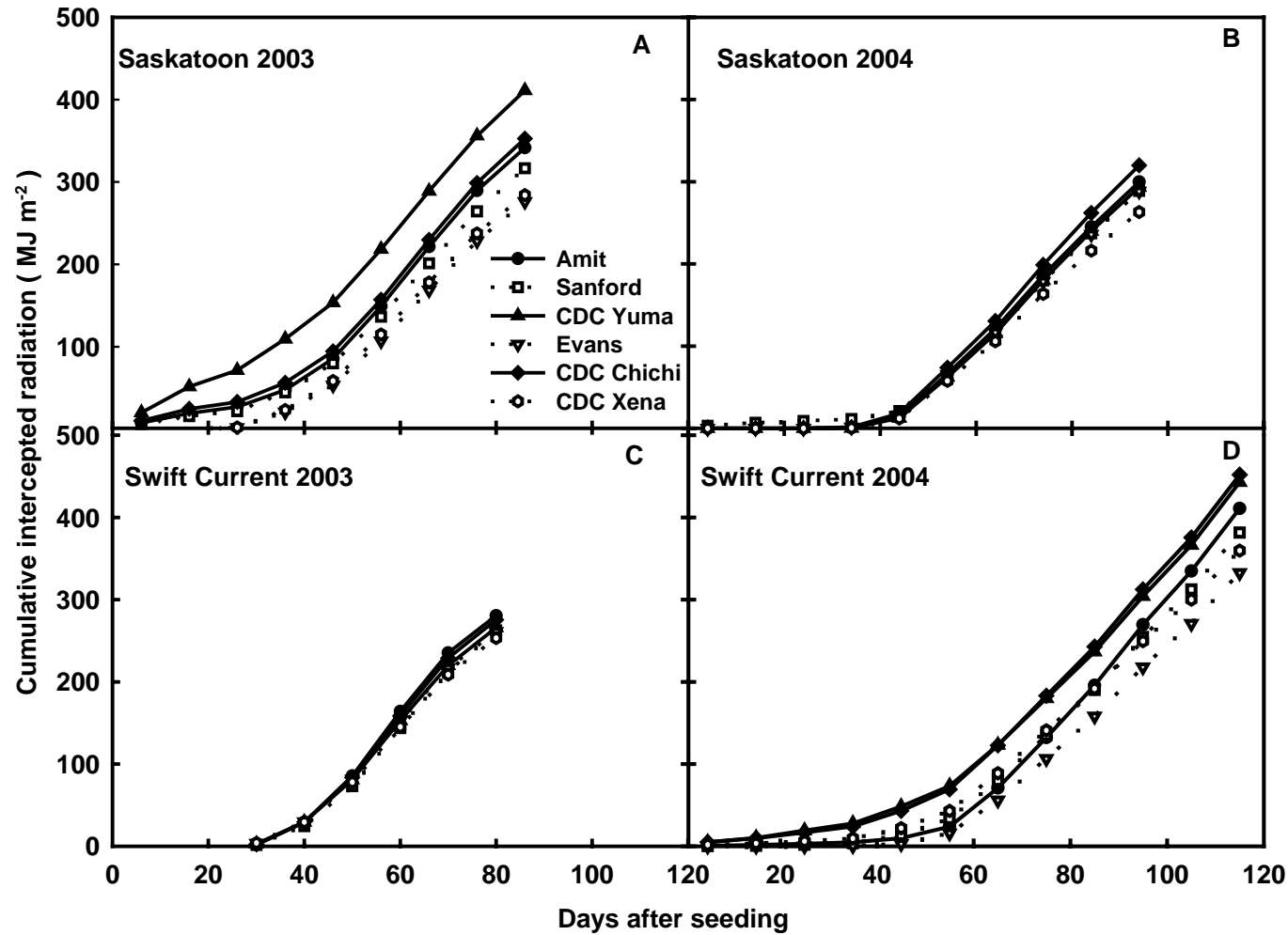
Figure 3.6 Cumulative intercepted radiation of six cultivars of kabuli chickpea as a function of days after seeding at four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively.

early until the end of the growing season in Swift Current (Figure 3.7). Of 85 plants m^{-2} had a greater cumulative intercepted radiation, during the whole growing season at Swift Current in both years and from the middle until the end of the growing season in Saskatoon 2003 (Figure 3.8). There was no difference at Saskatoon 2003 due to severe internal competition for water, when chickpea seeded in wheat stubble accessed lower soil moisture, coupled with the drought stress in 2003 (Gan et al., 2003b). The leaf type × plant population interaction was not significant for cumulative intercepted radiation at Saskatoon 2003 (Table 3.6), but a leaf type × plant population interaction was significant at Swift Current 2004. The combination of fern leaf and 85 plants m^{-2} was significantly higher than the other three combinations of leaf type and population. At 85 plants m^{-2} , the more upright leaves of fern-leaf cultivars allow better light penetration into the canopy compared to unifoliate-leaf cultivars. At 45 plants m^{-2}, fern-leaf cultivars exhibited more leaf area and had a closer canopy compared to the unifoliate leaf. Future high-yielding crops will likely come from fern leaf cultivars combined with higher plant population.

Seasonal cumulative intercepted radiation was within 269-463 MJ m^{-2} (Table 3.5), which is within the range of 284-562 MJ m^{-2} in New Zealand (Verghis, 1996). Leaf type and plant population interactions for seasonal cumulative intercepted radiation were not significant in four location-years (Appendix 9). The seasonal cumulative radiation intercepted by 85 plants m^{-2} was significantly higher than radiation intercepted by 45 plants m^{-2} in three out of four location-years. This result was in agreement with those of Hughes et al. (1987). Likewise, fern leaf had a
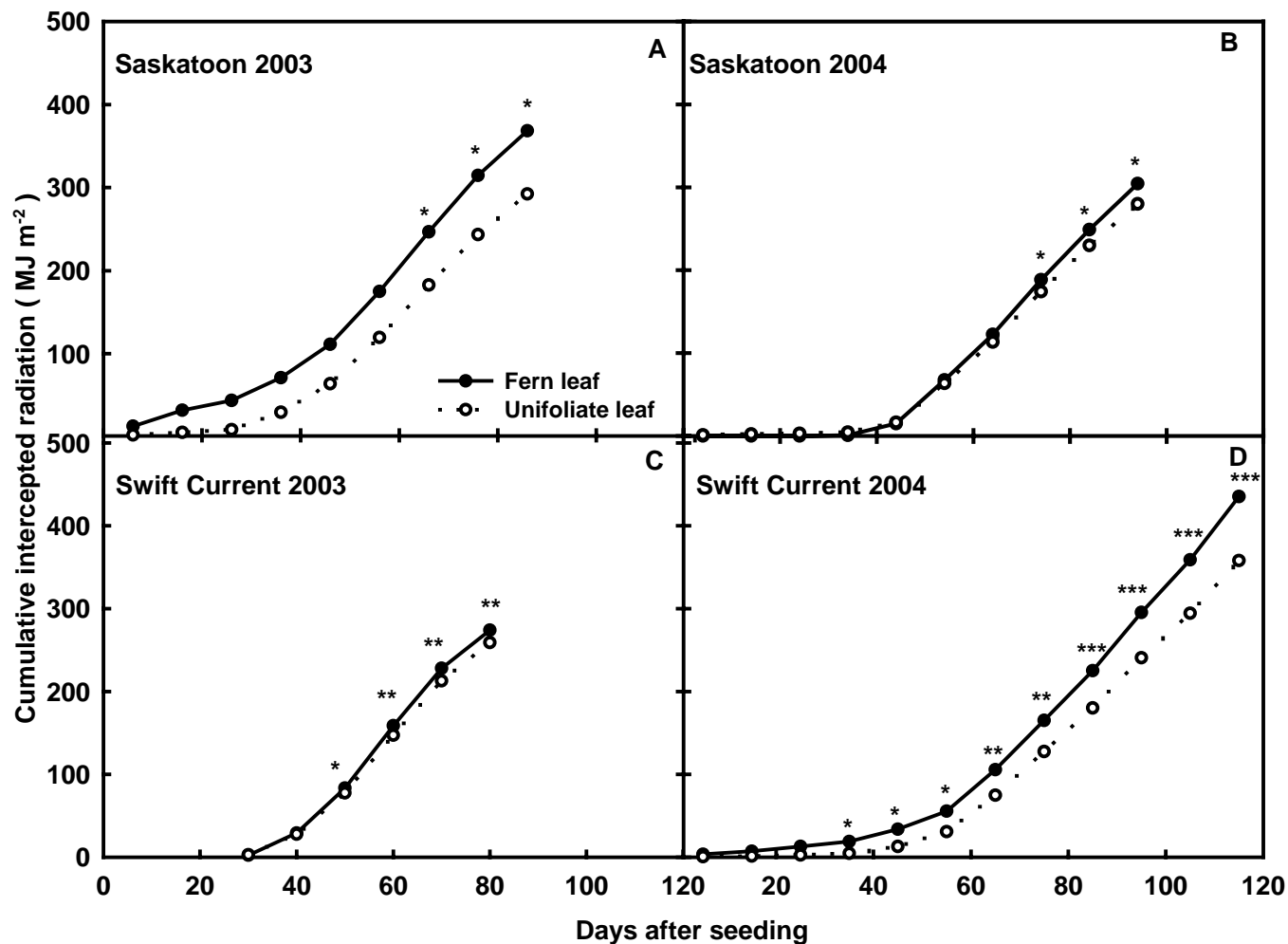
Figure 3.7 Cumulative intercepted radiation of fern-leaf and unifoliate-leaf canopy of kabuli chickpeas as a function of time at four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively. *, **, *** indicate that cumulative intercepted radiation differed significantly within a day between two leaf types at the 0.05, 0.01 and 0.001 levels of probability, respectively.

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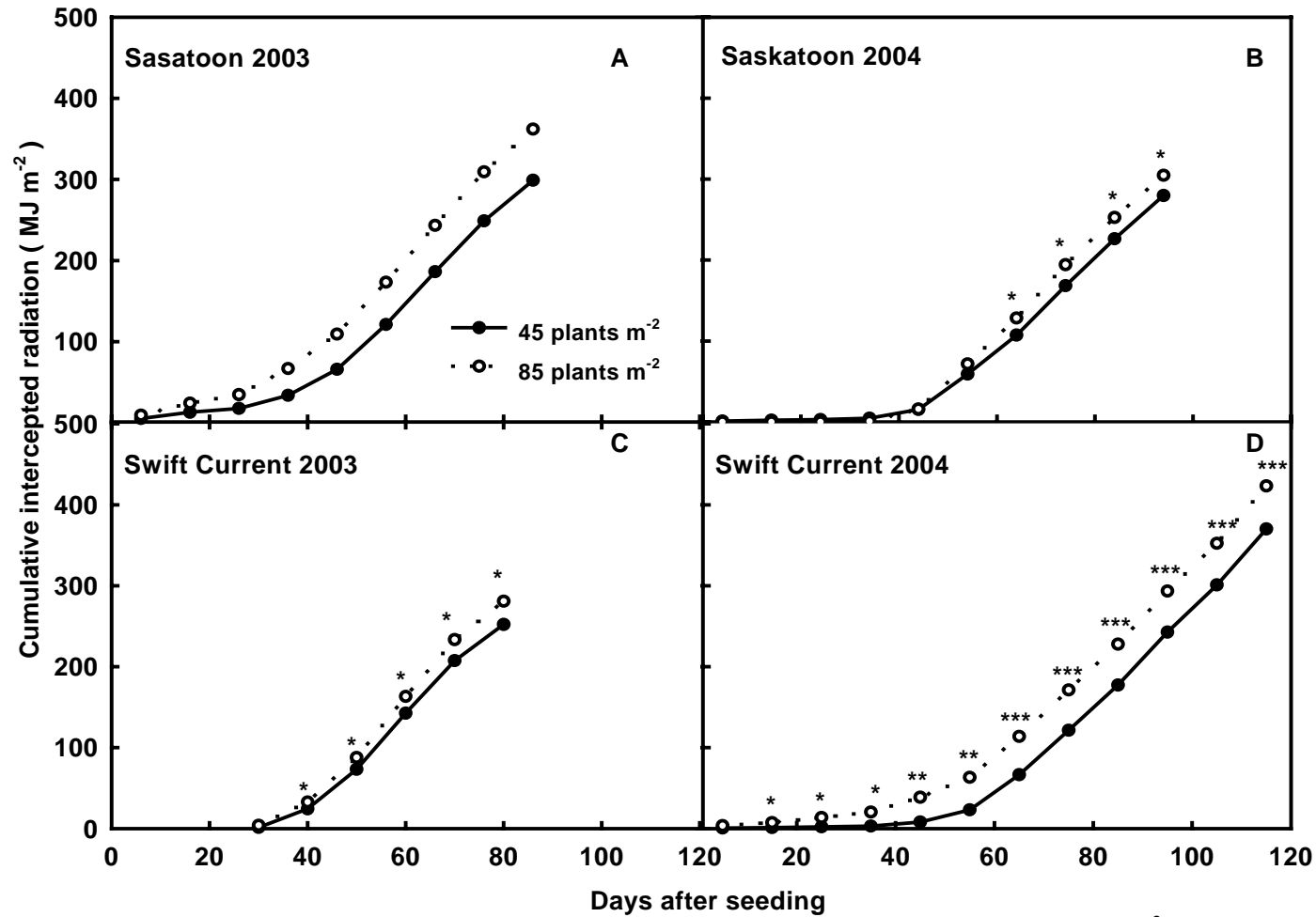
Figure 3.8 Cumulative intercepted radiation of kabuli chickpea canopy at two plant densities (45 plants m^{-2} and 85 plants m^{-2}) as a function of time at four location-years. Panel A, B, C, D represent Saskatoon 2003, Saskatoon 2004, Swift Current 2003, Swift Current 2004, respectively. *, **, *** indicate that cumulative intercepted radiation differed significantly within a day between two plant densities at the 0.05, 0.01 and 0.001 levels of probability, respectively.

Table 3.6 The effect of leaf type, plant population treatments in Saskatoon 2003 and Swift Current 2004 on cumulative intercepted radiation during the growing season.

Leaf type	Plant population	Cumulative Intercepted Radiation (MJ m^{-2})									
	(Plants m^{-2})	Saskatoon 2003				Swift Current 2004					
		44 DAS[‡]	55 DAS	62 DAS	71 DAS	54 DAS*	63 DAS*	73 DAS*	83 DAS*	94 DAS*	105 DAS*
Fern	85	120 aξ	191 a	251 a	310 a	87 a	133 a	196 a	256 a	329 a	400 a
	45	80 ab	142 ab	199 ab	273 a	17 b	54 b	112 b	172 b	247 b	318 b
Unifoliate	85	75 ab	139 ab	193 ab	247 ab	32 b	70 b	126 b	179 b	244 b	305 bc
	45	33 b	86 b	134 b	186 b	24 b	58 b	110 b	162 b	225 b	284 c

* indicates significantly interaction between leaf type and plant population.

[†] DAS is days after seeding.

ξ values within a column followed by the same letter are not significantly at the 0.05 probability level.

higher seasonal cumulative intercepted radiation than the unifoliate leaf in three out of four location-years.

3.3.7 Radiation use efficiency

Average RUE (Table 3.7) for chickpea dry matter was 1.22 ± 0.22 g MJ^{-1} intercepted radiation at Saskatoon and 1.24 ± 0.12 g MJ^{-1} intercepted radiation at Swift Current in the dry year 2003. Average RUE across the cultivars was 1.96 ±0.17 g. At Saskatoon 2003, CDC ChiChi had the highest RUE of all cultivars and was the only cultivar that differed significantly from the other cultivars. However, CDC ChiChi had the lowest RUE of all the cultivars and showed significant difference from both Evans and CDC Xena, at Swift Current 2003. At Saskatoon 2004, CDC Xena had a greater RUE than CDC ChiChi and Amit; CDC Yuma showed a significant difference from the other cultivars, except Evans.

Leaf type and plant population interaction were not significant in four location-years (Appendix 10). At Saskatoon 2003, RUE was significantly decreased by an increase of plant population from 45 to 85 plants m^{-2}. There was no significant difference between the two populations in the other three location-years. The same trends happened in soybean as Purcell et al. (2002), reporting a decrease in RUE with increasing density. Since biomass is the sink for nitrogen and the source of this nitrogen is foliage and soil nitrogen, the decrease in RUE can be due to the reduction of either photosynthetic ability of the canopy, or soil nitrogen or nutrient available. RUE decreases, as nitrogen stress increases, for both C3 and C4 crops (Sinclair and Horie, 1989). In the high plant population, canopy shading increases and availability N needs to be distributed across a greater leaf area,

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Table 3.7 Effect of leaf type and plant population on radiation use efficiency, harvest index and yield at Saskatoon and Swift Current in 2003 and 2004.

Cultivar and leaf type	Radiation Use Efficiency g MJ^{-1}				Harvest Index				Yield (Kg ha^{-1})			
	Saskatoon		Swift Current		Saskatoon		Swift Current		Saskatoon		Swift Current	
	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
Fern Leaf												
Amit	1.18	1.83	1.15	2.31	0.40	0.42	0.51	0.46	1083	1554	1072	3996
CDC ChiChi	1.67	1.75	1.13	2.31	0.45	0.33	0.47	0.37	1087	1160	908	3039
CDC Yuma	1.10	1.93	1.23	2.93	0.29	0.39	0.37	0.44	816	1327	640	3138
Unifoliate leaf												
Evans	1.22	1.99	1.40	2.61	0.30	0.26	0.31	0.15	715	857	703	864
Sanford	1.30	2.01	1.15	2.34	0.30	0.27	0.32	0.29	851	904	740	1807
CDC Xena	1.11	2.24	1.39	2.25	0.29	0.30	0.34	0.33	808	1005	762	1963
LSD (0.05)^z	0.31	0.33	0.26	0.52	0.08	0.07	0.04	0.07	151	121	82	196
45 plants m^{-2}	1.42	1.98	1.29	2.58	0.36	0.33	0.40	0.33	866	1109	789	2258
85 plants m^{-2}	1.11	1.94	1.19	2.33	0.32	0.33	0.37	0.35	920	1160	820	2677
Contrast for population	*	NS	NS	NS	*	NS	*	NS	NS	NS	NS	**
Fern leaf	1.32	1.84	1.17	2.52	0.38	0.38	0.45	0.42	995	1347	873	3391
Unifoliate leaf	1.21	2.08	1.32	2.40	0.30	0.28	0.32	0.25	791	922	735	1545
Contrast for leaf type	NS	*	NS	NS	*	**	**	**	**	**	**	**

*, ** indicate statistical significance at the 0.05 and 0.01 levels, respectively.

NS indicates no significant differences at P ≤ 0.05.

† LSD compares means between cultivars at each location year.

which in turn decreases the leaf N concentration and RUE (Purcell et al., 2002). A limitation of soil moisture at high population with chickpea seeded in wheat stubble (Gan et al., 2003b), can have the same effect on decrease RUE. However, this contradicts with the results of RUE in desi chickpea where RUE increased significantly, with the increasing of plant population in subhumid temperate Canterbury, New Zealand (Ayaz et al., 2004). It is most likely due to the difference in the growing season environment, compared to the prairies of Canada.

The unifoliate leaf had greater RUE in Saskatoon 2004 but was the same as the fern leaf in the other three-location years. It is not expected, as a canopy with erect leaves (fern leaf) will spend less time with highly light saturated leaves, than flat leaves (unifoliate leaf). The erectrophile canopy results in a higher RUE (Ayaz et al., 2004). Leaf orientation also needs to be considered, since it affects the amount of radiation absorbed (Taylor, 1975). Fern and unfoliate leaves may have different ability to adjust leaf orientation through the large diurnal cycle in northern latitudes.

3.3.8 Harvest index and yield

Leaf type and plant population interactions for harvest index were not significant in four location-years (Appendix 10). The fern leaf cultivars had a greater HI than the unifoliate leaf cultivars in all location-years (Table 3.7). Overall, Amit had one of the greatest HI values at all locations-years, while Evans had the lowest HI values in all locations-years. The 45 plants m^{-2} treatment had a greater HI than 85 plants m^{-2} at both locations in 2003 (Table 3.7), which may be due to high population density, increasing the lodging of barren plants (Weber et al., 1966).

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However, HI did not differ for plant population at Swift Current.

Leaf type and plant population interactions for yield were not significant in 2003 but significant in 2004(Appendix 11). Seed yield of fern leaf cultivars was greater than unifoliate leaf cultivars for all location-years. Plant population did not affect seed yield, except at Swift Current 2004, where 85 plants m^{-2} yields were significantly greater than 45 plants m^{-2} yields. Seed yield in 2004 was greater than in 2003 in both locations, due to the longer reproductive growth duration and higher rainfall. There was no significant cultivar and plant population interaction effect on seed yield.

Generally, a crop seeded in wheat stubble would have access to lower reserves of soil moisture, than summerfallow in dry environment conditions (Gan et al., 2003b). All cultivars grown on wheat stubble in 2003 in our study, had higher yield than cultivars grown on summerfallow, which maybe due to improved seeding and combine harvest efficiency, on wheat stubble (Miller et al., 2002). The difference in yield between two leaf types can be associated with high efficiency of dry matter partitioning, or higher HI (Table 3.7), higher CGR (Table 3.4), longer reproductive duration of growth (Table 3.3), higher growing season rainfall (Table 3.1) or a combination of these. However, CGR was inconsistent for locations and years and the longer growth season of 2004 is very uncommon in the short growing season in the Northern Great Plains.

3.4 Discussion

Fern leaf cultivars had significantly higher light interception than unifoliate leaf cultivars. An exponential function has been used previously to describe the

relationship between light interception and leaf area index (LAI) in grain legumes (Ayaz et al., 2004). A LAI of 3.5 to 4.0 was necessary to reach 90%-95% light interception in New Zealand (Ayaz et al., 2004). The fern leaf has a higher LAI than the unifoliate leaf, because full light interception (larger than 90%) was only achieved from fern leaf cultivars in 2004 from the data in this thesis.

Sivakumar (1978) and Ogbuehi and Brandle (1981), reported a linear relationship between the amount of number of leaflets per plant and the plant leaf area in soybean. A fern leaf has more small leaflets per plant from visual observation, therefore a larger plant leaf area than the unifoliate leaf. This is consistent with the results that leaf number is more important compared to leaf size in controlling LAI, and the rate of canopy closure by a chickpea crop (Siddique, 1984). Furthermore, a fern leaf has narrower lobes and more inclined leaf angle from the horizon compared to its unifoliate counterpart. This allows light penetration to a greater depth within the canopy and therefore, increases pod set in the lower layer of the crop and yield (Singh, 1991).

Kerby et al. (1993) found some modern cotton cultivars had small leaf areas of subtending leaves to the cotton plant, which caused a source-sink problem. The reduced leaf area in cotton genotypes had limited canopy photosynthesis and yield (Kerby et al., 1980; Wells et al., 1986). In chickpea, subtending leaves of developing pods appear to be the main source of photosynthate for the corresponding pods (Pandey, 1984). Unifoliate leaf cultivars have smaller subtending leaves and they produced less photosynthate for the subtending pod than fern leaf cultivars, which resulted in lower yield. The yield difference between two

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leaf types was strongly related with maximum light interception, cumulative
intercepted radiation and CGR, similar to soybean (Ball et al., 2000).

Higher plant population produced higher biomass and cumulative
intercepted radiation, which confirmed a previous study in chickpea (Siddique et al.,
1984). A highly significant positive relationship was found between cumulative
intercepted radiation and biomass production in lentil, in New Zealand (Mckenzie
and Hill, 1991). In this thesis, the highest yielding cultivars did not have the largest
seasonal cumulative intercepted radiation. However, when cultivars developed
relatively large yields but did not intercept correspondingly greater amounts of
radiation, the HI value was high (Table 3.5 and Table 3.7) and contributed to the
yield gain.

Higher plant population gave higher light interception from early growing
season until the middle of growing season, which meant an earlier canopy closure as
reported in other studies (Ayaz et al., 2004) including higher seasonal cumulative
intercepted radiation. However, a higher plant population only caused significant
yield increase at Swift Current 2004, otherwise, high plant population was neutral.
Elmore (1998) found that yield of an indeterminate soybean cultivar was unaffected,
as seeding population increased from 11 to 35 seeds m^{-2}. However, higher plant
population caused higher dry matter production in the other three location-years.
Harvest index was relatively constant at Saskatoon in 2004 and declined in 2003 at
high plant populations, due to interplant competition and lower rainfall from
drought. This is consistent with the results from Ayaz et al. (1999) that HI of
chickpea and field pea were relatively constant or declined at the highest plant

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population. Siddique et al. (1984) found that increased total biomass of chickpea at higher densities was compensated for by reduced HI and resulted in little change in yield. The lower HI of the crop at high population density, might be due to the low HI of the later appearing branches (Siddique et al., 1984). They also proposed that by coordinating biomass accumulation more closely with reproductive development, the lower HI from late season growth would be avoided.

Yield production by six cultivars did not reflect closely differences in RUE in our study. Highest yielding cultivars did not always have the highest RUE. The difference in RUE seemed to correspond with year, being high in the wet year and lower in the dry year. Cultivars with higher yield but relatively low RUE were compensated by relatively higher seasonal cumulative intercepted radiation or higher HI. Other studies, have observed only small difference in RUE among different yielding accessions on the Darling Downs of Southern Queensland (Leach and Beach, 1988). However, Ayza et al. (2004) found that RUE is the key determinant of chickpea yield in a cool-temperate, subhumid climate. In all the factors that contribute to the chickpea yield production, HI appears to be the determinant in Saskatchewan.

The value of RUE at both locations in 2003 appears to be reasonable for the six cultivars and within the range of values reported in the literature (Table 2.1). However, the values in 2004 were much higher than those reported. This may be attributed to differences in the estimation of PAR from measurement of total solar radiation. I assumed 50% of solar radiation was PAR, but in other records, a value of 45% had been used (Thomas and Fukai, 1995). This 45% value is unusually low.

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Due to the variable nature of RUE (Loomis and Amthor, 1999), estimation of RUE can be strongly influenced by minor differences in experimental protocols (Gallo et al., 1993). The RUE of chickpea can be affected by factors such as sowing date (Hughes et al., 1987; Anwar et al., 2003), crop cultivars (Tollenaar and Aguilera, 1992), plant population (Ayza et al., 2004), plant growth habit (Hughes et al., 1987), and row spacing (Leach and Beech, 1988) as well as irrigation (Leach and Beech, 1988; Singh and Sri Rama, 1989; Thomas and Fukai, 1995; Anwar et al., 2003), site, season (Hughes et al., 1987), minimum temperature (Bell et al., 1993) or temperature (Kiniry et al., 2001) coupled with radiation level, disease and stress (Thomson and Siddique, 1997; Loomis and Amthor, 1999). Sample size and nutrient status of the crop, that is, any environment of the experiment that limits the expression of higher RUE (Sinclair and Muchow, 1999), can cause low RUE values. In our experiment, water deficits during the 2003 growing season decreased the RUE, and similar results can be found in other environments like the Mediterranean (Hughes et al., 1987; Thomson et al., 1997) and a semi-arid tropical environment (Singh and Sri Rama, 1989).

4.0 Assessing the leaf type under defoliation, shading and light enrichment

4.1 Introduction

Solar radiation availability is one of the most significant factors affecting plant yields. Yield of crops, including chickpea, is directly related to the amount of intercepted radiation (Monteith, 1977; Ayaz et al., 2004). In a short growing season the total cumulated solar radiation is seldom adequate for optimal plant growth. Therefore, reduced solar radiation in some years can affect chickpea growth and productivity by reducing the amount of intercepted solar radiation (Verghis et al., 1999). In addition, seasonal fluctuations in climate create serious risks to chickpea production in the Northern Great Plains (Padbury et al., 2002).

Yield of chickpea is the net result of production of photosynthetic assimilates mainly by leaves, the source, and the subsequent translation of these assimilates to the seed, the sink by current day fixation or remobilization of previously fixed carbon (Singh and Pandey, 1980). Timing, intensity, frequency and duration of decreased assimilate supply in defoliation and shading studies has demonstrated changes to chickpea yield (Sheldrake et al., 1978; Pandey, 1984; Verghis et al., 1999). Strategies to improve yield in chickpea should focus on removing any apparent limitation of cumulated radiation during specific development periods. For example, chickpea yield may be more affected by altered

source strength (leaf area and light interception) during the vegetative period, during early season leaf expansion or during reproductive growth. If the mechanism behind a source-sink restriction is understood then the allocation of assimilates within a specific critical period may be increased, thereby increasing yield.

Sheldrake et al. (1978) varied the extent of defoliation from flowering to maturity using sequential defoliation and found that yield was significantly reduced in proportion to the degree of defoliation. In contrast, Pandey (1984) altered source strength by using both single-day and sequential partial defoliation from pre-anthesis to maturity, and found that yield reduction was not proportional to the degree of defoliation. Verghis et al. (1999) showed that reduction in light interception by 40% shading from the beginning of plant emergence to plant maturity delayed the time to achieve a critical leaf area index of 3.0. This limited biomass production and caused significant yield reduction. In contrast, Sheldrake et al. (1978) imposed shading during reproductive growth and concluded that 50% shading did not affect yield. Only 80% shading decreased yield.

Most of the published studies have differential responses to reduction in light quantity by defoliation and shading. No study has been conducted on nondestructive light enrichment although light enrichment can be easily achieved by exposing rows to greater light and nutrient conditions. Light enrichment has been used in soybean and cotton (Mathew et al., 2000; Pattigrew, 1994). Moreover, little is known about the dynamics of intercepted radiation, biomass accumulation and crop growth rate (CGR) in chickpea. In addition the effects of incident radiation on key physiological parameters have been studied independently of the effects of leaf

morphology. Morphological differences can cause an alteration in the quantity of transmitted light that reaches the soil due to different branching patterns and canopy architecture (Singer and Meek, 2004). In canopy attenuation, different crops have different extinction coefficients depending on their leaf shape, leaf inclination, leaf area index and branching (Jones, 1992). Various leaf types respond differently to alterations in the source-sink relationship. For instance, the super-okra (deeply palmate) leaf in cotton had the greatest response to early-season square (immature flower bud) removal compared to the okra and normal leaf type (Kennedy et al., 1986). In soybean, narrow-leaflet isolines had greater light interception compared to their wide-leaflet counterparts after similar defoliation (Haile et al., 1998). A narrow-leaflet isoline was relatively more tolerant to defoliation than three other leaflet isolines.

The unifoliate and fern leaf types in chickpea may differ in terms of leaf area, light interception, crop growth and yield. One type may be more sensitive but only at particular stages of crop growth. If one of the leaf types is superior to the other, then defoliation of the canopy or shading will reduce the amount of light intercepted, and thus influence growth and yield. The objectives of this study were to: (1) investigate the effect of changes in the quantity of light created by shading, defoliation or enrichment on chickpea canopy development, biomass accumulation, CGR, radiation intercepted, harvest index (HI) and yield; and (2) determine any differential responses associated with the fern and unifoliate leaf in source-sink manipulation. This information may elucidate the best leaf type for early season, mid season, or late season growth and yield.

4.2 Materials and Methods

4.2.1 Experimental design, location and management

Field experiments were conducted in 2003, 2004 and 2005 at Goodale Research Farm (52.1' N, 106.41' W) and Agriculture and Agri-Food Canada Swift Current Research Centre (50.2' N, 107.4' W). At Goodale the soil was a Dark Brown Chernozem (Typic Borolls), and at Swift Current the soil was an Orthic Brown Chernozem (Aridic Haploborolls). The experiment was a randomized complete block design with four replications. Three blocks were used at Goodale in 2005 because of severe disease at seedling emergence in the fourth block. A factorial combination of two cultivars (Sanford with the unifoliate leaf and CDC Yuma with the fern leaf) and either four canopy treatments (in 2003) or six canopy treatments (in 2004 and 2005) were used. In Saskatchewan Sanford typically yields 1312 kg ha^{-1} with an individual seed size of 9 mm and seed weight of 425 g 1000 seed^{-1} and CDC Yuma typically yields 1482 kg ha^{-1} with an individual seed size of 9 mm and seed weight of 410 g 1000 seed^{-1} (Anonymous, 2001).

Seeds were sown at 98 seeds m^{-2} for a target of 85 plants m^{-2} at typical Saskatchewan seeding dates (Table 4.1). The plant population density was high in order to generate rapid canopy development; 45 plants m^{-2} is the typical recommended density (Gan et al., 2003b). Seed was inoculated with commercial rhizobial inoculant before sowing and sown at 50 mm depth with a row spacing of 0.3 m. At Saskatoon, plot size was 8 rows wide (2.4m) by 4.88 m long in 2003 and 2004, and 16 rows wide (4.9 m) by 4.9 m long in 2005. At Swift Current, plot size

Table 4.1 The mean date for the main phenological stages of CDC Yuma and Sanford in 2003, 2004 and 2005 at Saskatoon and Swift Current. Figures in parentheses are Day of Year

Year	Location	Seeding	Emergence	First Flowering	Maturity
2003	Saskatoon	May 14th (134)	May 29th (149)	June 30th (181)	August 11th (223)
	Swift Current	May 20th (140)	May 30th (150)	June 30th (181)	August 12th (224)
2004	Saskatoon	May 25th (146)	June 10th (162)	July 19th (201)	October 28th (302)
	Swift Current	May 16th (137)	June 1st (153)	July 14th (196)	October 4th (278)
2005	Saskatoon	May 12th (132)	June 1st (152)	July 7th (188)	October 5th (278)
	Swift Current	May 10th (130)	May 26th (146)	July 7th (188)	September 2nd (245)

was 6 rows wide (1.8 m) by 6.7m long in 2003 and 2004, and 12 rows wide (3.7 m) by 4.9 m long in 2005. About four weeks after sowing, plant density was estimated by counting 1 m length of a random middle row at two positions in each plot; In-season stand check was not seen. At Saskatoon in 2003, weeds were managed with ethalfluralin (Granular Edge) at a rate of 28 kg ha^{-1} applied in the spring before seeding. Pre-emergence herbicide imazethapyr (Pursuit) at a rate of 0.07 L ha^{-1} was applied for weed control. The fungicides chlorothalonil (Bravo) at a rate of 3.2 L ha^{-1} and pyraclostrobin (Headline) at a rate of 0.4 L ha^{-1}were applied to control fungal disease ascochyta blight. Bravo was used when chickpea plants began flowering, and thereafter Headline was used twice at 10-day intervals. In 2004, weeds at Saskatoon were controlled using a pre-seeding application of ethalfluralin plus a pre-emergence application of imazethapyr. Application of chlorothalonil was used at initial flowering, followed by two sprays separated by 10-day intervals of pyraclostrobin at the same rate used in 2003. In 2005, the same herbicide and fungicide applications were applied as in 2003 and 2004 plus a pre-seeding application of clethodim (Centurion) at a rate of 0.20 L ha^{-1}.

At Swift Current in 2003, weeds were controlled using a pre-seeding application of ethalfluralin (Granular Edge) at a rate of 17 kg ha^{-1} on 8 May, a pre-emergence application of glyphosate (Roundup) at a rate of 2.5 L ha^{-1}, and imazethapyr (Pursuit) at a rate of 0.03 L ha^{-1} on 21 May, and a post-emergence application of sethoxydim (Poast Ultra) at a rate of 0.48 L ha^{-1} on 17 June. Four applications of fungicide were used in 2003 to control ascochyta blight including pyraclostrobin (Headline) at 0.40 L ha^{-1} on 27 June and 11 July, and chlorothalonil

(Bravo) with the rates of 4.0 L ha^{-1} on 18 June and 3.0 L ha^{-1} on 24 July at Swift Current in 2003.

In 2004, weeds at Swift Current were managed with a pre-seeding application of ethalfluralin on 26 April with supplemental pre-emergence application of glyphosate (Roundup) at a rate of 0.88 L ha^{-1} and imazethapyr (Pursuit) at a rate of 0.03 L ha^{-1} on 20 May, as well as a post-emergence application metribuzin (Sencor) at a rate of 0.30 L ha^{-1} on 9 June. In 2005, weed control consisted of a pre-seeding application of ethalfluralin on 19 April, and a pre-emergence application of glyphosate and imazethapyr on May 19. The fungicide pyraclostrobin was applied to manage ascochyta blight on 27 June, 21 July combined with two applications of chlorothalonil on 21 July with the rate of 4.0 L ha^{-1} and 3 August with the rate of 3.0 L ha^{-1}, respectively.

Grasshoppers were controlled in 2003 at both Saskatoon and Swift Current. Chlorpyrifos (Lorsban) was sprayed twice at a rate of 1L ha^{-1} during reproductive growth (early flowering and mid pod-fill) at Saskatoon, and dimethoate (Cygon) was sprayed at first flower at a rate of 0.5 L ha^{-1}.

4.2.2 Experimental procedures

In 2003, four canopy treatments were applied to provide a diversity of incident radiation during different growth stages (Table 4.2). These were: (1) the untreated control; (2) 50% defoliation during vegetative growth; (3) 50% defoliation commencing when 50% of the plants within a plot first had their first open flower. Both defoliation treatments were performed by removing leaves alternately on both

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Table 4.2 Experimental treatments: dates of defoliation, light enrichment and dates of beginning and end of shading in 2003, 2004 and 2005 at Saskatoon and Swift Current. Figures in parentheses are Day of Year.

Treatment		2003		2004		2005	
VEGDEF	Saskatoon	June 20th (171)		June 29th (181)		July 1st (182)	
	Swift Current	June 19th (170)		June 30th (182)		June 30th (181)	
FLWDEF	Saskatoon	July 2nd (183)		July 21st (203)		July 13th (194)	
	Swift Current	July 3rd (184)		July 26th (208)		July 11th (192)	
FLWENR	Saskatoon	NA		July 20th (202)		July 14th (195)	
	Swift Current	NA		July 26th (208)		July 12th (193)	
PODENR	Saskatoon	NA		August 6th(219)		July 22nd (203)	
	Swift Current	NA		August 5th (218)		July 20th (201)	
SHADING		Beginning	End	Beginning	End	Beginning	End
	Saskatoon	June 18th (169)	July 2nd (183)	July 6th (188)	July 21st (203)	July 5th (186)	July 22nd(203)
	Swift Current	June 17th (168)	July 3rd (184)	July 9th (191)	July 23rd (205)	June 30th (181)	July 20th (201)

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

main stem and all branches to reach about 50% of removed leaf area. Fifty percent

defoliation was representative of the intensity of foliage damage caused

by insects and disease in the field (Pandey et al., 1984). The final treatment (4)

shading, was achieved with black commercial shade cloth (PAK unlimited, Inc.

Willacoochee, GA) stretched just above the chickpea canopy on cages and anchored

by eight stakes. The shade cloth intercepted 45% of the incident photosynthetically

active radiation (PAR) from the vegetative stage (treatment 2) to the beginning of

flowering. Canopy treatments were applied for two weeks, except for Swift Current

in 2005, where treatments were applied for three weeks. In 2004 and 2005, two

additional treatments were included: light enrichment initiated at first flower (5) and

light enrichment initiated at the pod formation stage (6). Both light enrichment

treatments, once started, lasted until final harvest. The light enrichment treatments

were achieved by installing 0.5 m high chicken wire fencing of either side of two

rows, which pushed down on neighboring rows at a 45$^\mathrm{o}$ angle from the center two

rows (Mathew et al., 2000). The wire fencing prevented encroachment of plants

from adjacent rows into the center two rows' growing space, and thus increased

light interception, especially at the base of the canopy. This maintained water and

nutrient competition with plants from adjacent rows. At weekly intervals, the fences

were checked for leaf and pod regrowth; any regrowth from the held back rows was

pushed behind the fences where necessary.

4.2.3 Measurements and calculation

Plots were measured by sampling interior plants. The outside rows were

considered unsampled borders, as were the top and bottom 0.3 m deep edges.

Biomass was sampled at the time of each treatment initiation and the end of the treatment, beginning at approximately the fourth-node stage, until plant physiological maturity. Above-ground biomass was sampled from the center four adjacent rows (total of 0.3 m^2 per plot), and 0.3 m away from any previous biomass sample. Samples were dried at 60 ^{o}C for 7 d and weighed. Crop growth rate during two sampling dates was calculated by biomass difference between the two sampling dates and divided by the number of days within the corresponding period. Light interception was measured on the same day as the biomass sample taken by using a 1-m long Licor Line Quantum sensor (Model LI-191SA, Lincoln, NE) connected to a light meter. Measurements were taken between 1130 and 1500 h solar time. The line quantum sensor was positioned above the canopy for one reading, and then placed on the ground across the plot rows, perpendicular to the row length. Two readings were taken parallel to the ground reading, but at a random position. For the shading treatment, the canopy was measured by taking one reading above the shading cloth followed by another three readings under the canopy. The canopy under the two light enrichment treatments was not measured, because there was not a light measurement technique available.

The fractional light interception by the canopy was determined by using the following equation:

Light interception = [1-(PAR beneath canopy) ×(PAR above canopy)$^{-1}$] [4.1]

The maximum light interception achieved by a plot within the growing season was calculated as below. Canopy light interception (MJ m $^{-2}$ d $^{-1}$) for each day of the experiment for a given plot was calculated by modeling, for each plot, the

actual light interception against days of experiment. This allowed a predicted light interception value for any day of the experiment. Light interception as the independent variable was regressed against day of experiment in a linear, quadratic or cubic model. The cubic model was chosen based on the best-adjusted R^2 values. The R^2 values for the cubic models used varied from ≥ 0.80 to 0.99. The predicted daily fractional light interception was multiplied by daily total radiation for each day of the experiment. Daily total radiation is equal to one half of daily incident radiation, which was measured from the pyranometer on a nearby-automated weather station (500 m in an adjacent durum field for all locations). Intercepted radiation was then cumulated for each plot from emergence to physiological maturity. Daily air temperature and mean daily incident radiation were also recorded from the automated weather station in Saskatoon and a standard meteorological station at Swift Current.

Six plants per plot were randomly sampled from the central two rows at physiological maturity. Seeds and straw were dried in an oven at 40 $^{\circ}$C for 7 to 10 d and weighed separately. Harvest index was calculated as the ratio of seed yield to total above-ground biomass. Plant height and the lowest pod height were also measured from three random plants in each plot at physiological maturity. Plant height was the distance from the ground to the shoot meristematic apex. The lowest pod height was measured from the ground to the lowest visible pod. Yield was combine harvested at physiological maturity from interior rows. At Saskatoon, the harvest area of each plot was 7.1 m^2 in 2003, 6.8 m^2 in 2004, and 6.0 m^2 in 2005. At Swift Current, they were 7.9 m^2 in 2003, 6.8 m^2 and 6.0 m^2 in 2005. Chickpea

from two light enrichment treatments were hand-harvested in 2004 and 2005 from

the unsampled, light enriched rows in each plot. The harvest area of each plot was

3.0 m^2 at Saskatoon and 2.1 m^2 at Swift Current in 2004. In 2005, 3.0 m^2 was

harvested at both locations. Harvested seeds were dried at 60 ^{o}C for a week,

cleaned and weighed for seed yields.

4.2.4 Statistical analysis

Analysis of variance was performed on measured and calculated variables

using the general linear model procedure (PROC GLM) of SAS (Version 8.2, SAS

Inst., 1999), for each location-year separately, due to large variations in weather

from year to year. Mean separation was done by using Fisher's protected least

significant difference (LSD) at the 0.05 level of significance, to establish the

significance of main effects and any interaction. Chickpea cultivars and light

treatments were considered as fixed effects.

4.3 Results

4.3.1 Growth conditions

The 2003, 2004 and 2005 growing seasons (Table 4.3) provided very distinct

growing environments. Growing season precipitation and temperature were quite

variable among the three Saskatoon environments. Precipitation amounts (May

through September) were 57 mm below average for the 2003 environment and 59

and 198 mm above average for the 2004 and 2005 environments, respectively.

Despite the below-average precipitation at the Saskatoon 2003 environment,

temperatures at this environment were near normal in 2003. In 2004 at Saskatoon,

Table 4.3 Monthly maximum, minimum and mean air temperature, cumulative monthly precipitation during 2003, 2004 and 2005 at Saskatoon and Swift Current.

Month	Saskatoon				Swift Current			
	Maximum temperature (^{o}C)							
	2003	2004	2005	30-year average†	2003	2004	2005	30-year average
May	19.9	14.7	16.6	18.4	17.2	13.9	16.3	17.9
June	23.1	18.9	19.3	22.6	21.1	18.8	19.7	22.2
July	25.7	22.8	24.5	24.9	27.8	23.8	25.2	24.9
August	28.4	20.1	22.2	24.4	28.9	21.2	23.3	24.6
September	17.7	18.2	19.1	18.0	17.7	18.6	19.0	18.1
	Minimum temperature (^{o}C)							
May	3.6	1.1	3.0	4.5	4.7	2.7	3.4	4.2
June	8.7	7.1	9.8	9.4	9.2	7.3	9.8	8.7
July	10.6	11.1	11.4	11.4	11.8	11.8	11.9	10.8
August	12.7	7.7	9.1	10.2	14.0	9.4	9.7	10.1
September	4.8	5.8	8.3	4.4	5.9	6.1	5.9	4.6
	Mean air temperature (^{o}C)							
May	11.8	7.9	9.8	11.5	11.0	8.3	9.8	11.0
June	15.9	13.0	14.6	16.0	15.1	13.0	14.7	15.5
July	18.2	18.3	18.2	18.2	19.8	17.8	18.6	17.9
August	20.6	15.1	15.5	17.3	21.5	15.3	16.5	17.4
September	11.3	11.8	11.7	11.2	11.8	12.3	12.5	11.4
	Rainfall (mm)							
May	13.8	36.0	27.6	46.8	41.9	83.7	22.4	45.3
June	30.8	86.6	173.2	61.1	78.7	66.2	123.2	67.9
July	63.9	74.8	57.0	60.1	8.3	61.1	21.4	55.2
August	31.4	73.0	84.0	38.8	20.7	72.3	52.1	43.5
September	38.7	24.5	92.4	29.0	39.0	27.4	40.7	26.6

†from 1974 to 2003

precipitation was high in June, followed by above-average precipitation in July and August and below-average precipitation in September. Temperatures were cooler than normal throughout the growing season at Saskatoon, with the exception of September, which was near normal. Similarly, rainfall was considerably greater than average in June at Saskatoon in 2005, followed by relatively below-average precipitation in July and above-average precipitation in August and September. Swift Current had similar weather as Saskatoon in 2003 and 2004, except that the early growing season was dry in Swift Current during May (48 mm below Saskatoon) in both years. The rainfall pattern of Saskatoon was similar to Swift Current in 2005. Both the minimum and mean air temperature was below average during May and June in 2005 at both locations, followed by normal temperature during July, August and September. All the climatic factors and timing had effects on chickpea development.

4.3.2 Plant population density

Generally, plant populations were below the target plant population of 85 plants m^{-2} (Table 4.4). There were no significant cultivar × treatment interactions for plant population density in all the six location-years (Appendix 12). Plant populations averaged across cultivar and treatment were 67, 71, and 65 plants m^{-2} at Saskatoon in 2003, 2004 and 2005 respectively. Plant populations averaged across cultivar and treatment were 72, 53 and 75 plants m^{-2} in Swift Current in 2003, 2004 and 2005 respectively.

In two out of three years, Swift Current had higher plant populations than Saskatoon, except 2004 where plant population was quite low. At Saskatoon, plant

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Table 4.4 Population density (PPD) after emergence for kabuli chickpea grown at Saskatoon and Swift Current in 2003, 2004 and 2005.

Treatment Factors		Target PPD (plants m^{-2})	Actual Plant Population Density (plants m^{-2})					
			2003		**2004**		**2005**	
			Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
Cultivars								
	Sanford (Unifoliate)	85	70	73	66	54	61	73
	CDC Yuma (Fern)	85	63	71	74	51	68	77
	LSD (0.05)		6	NS	4	NS	6	4
Treatments								
	Control	85	63	76	70	51	69	78
	VEGDEF	85	66	72	68	53	65	76
	SHADE	85	69	71	70	52	65	73
	FLWDEF	85	68	70	70	54	65	71
	FLWENR	85	NA	NA	72	49	62	77
	PODENR	85	NA	NA	70	54	63	76
	LSD (0.05)		NS	NS	NS	NS	NS	NS

NA indicates FLWENR and PODENR treatments are not available.

NS indicates no significant differences at P ≤ 0.05.

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

population for the cultivars differed in three years whereas Swift Current cultivars'
populations were similar. No differences in plant population were found among the
six canopy treatment regimes in any of the six location-years. CDC Yuma had
higher plant populations than Sanford in 2004 and 2005, but lower populations in
2003. The possible explanation for cultivar differences at Saskatoon may be seed
lot viability and quality varying from 2003 and 2004. In 2005, early ascochyta
blight infection reduced plant population in Sanford, a more susceptible cultivar
compared to CDC Yuma.

4.3.3 Plant height

There were no significant cultivar × treatment interactions for plant height in
any of the six location-years (Appendix 13). Plant height was affected by cultivar
(Table 4.5); Sanford was taller than CDC Yuma at Swift Current in 2003 and 2005.
Nevertheless, they had similar plant height at harvest in the other location-years
(Table 4.5). Moreover, CDC Yuma had pods closer to the ground (lowest pod
height) than Sanford at Swift Current in three years and at Saskatoon in 2004; the
trait of the lowest pods being higher on a plant can benefit combine harvesting.
Canopy treatment affected plant height in 2003 irrespective of location. The
shading treatment resulted in taller plant height and increased pod height than the
three other canopy treatments. In 2004, although not statistically significant, plant
height of the shade treatment was greatest among different canopy treatments at
Saskatoon. Shading resulted in significantly taller plant height compared to the
other five canopy treatments at Swift Current. In 2005, reduced plant heights were

Table 4.5 Plant height (cm) and lowest pod (LP) height for six canopy treatments and two kabuli cultivars, CDC Yuma and Sanford in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Year	2003				2004				2005			
Location	Saskatoon		Swift Current		Saskatoon		Swift Current		Saskatoon		Swift Current	
Treatment	Plant	LP	Plant	LP	Plant	LP	Plant	LP	Plant	LP	Plant	LP
							(cm)					
Control	35.4	26.5	38.1	22.9	54.2	30.1	62.1	32.2	69.2	32.6	59.1	32.3
VEGDEF	37.0	25.9	35.9	21.9	51.4	28.9	64.8	31.3	62.8	31.5	55.1	30.8
FLWDEF	38.6	25.8	37.6	24.0	54.8	29.9	61.7	31.5	57.5	32.7	57.9	31.5
SHADE	44.4	32.3	48.1	31.5	57.1	32.9	72.4	34.4	56.1	32.6	59.8	35.6
FLWENR	NA	NA	NA	NA	53.5	31.3	60.5	34.4	60.2	33.3	59.5	32.4
PODENR	NA	NA	NA	NA	52.8	30.4	60.9	30.5	57.0	30.3	58.1	33.0
LSD (0.05)	4.0	3.1	3.0	2.2	3.5	2.9	6.0	3.5	8.0	NS	3.2	3.0
Cultivar												
CDC Yuma (Fern)	39.3	27.0	37.6	23.1	54.2	29.2	62.5	30.2	58.3	33.0	56.9	31.6
Sanford (Unifoliate)	38.5	28.2	42.3	27.0	53.8	32.0	64.9	34.6	62.6	31.1	59.6	33.6
LSD (0.05)	NS	NS	2.1	1.6	NS	1.7	NS	2.0	NS	NS	1.9	1.7

NA indicates FLWENR and PODENR treatments are not available.
VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.
NS indicates no significant differences at $P \leq 0.05$.

observed in all the canopy treatments compared to the control at Saskatoon. However, at Swift Current, only the vegetative defoliation had a shorter plant height than the control, and the other treatments had similar plant heights compared to the control. Canopy treatments had no effect on the lowest pod height in 2004 and 2005, irrespective of location.

4.3.4 Biomass production over time and maximum biomass

There were no significant cultivar × treatment interactions for biomass accumulation at most of the sampling dates in the six location-years (Appendix 14). At Saskatoon in 2003 and 2004, biomass accumulation (Figure 4.1) was similar in CDC Yuma (fern) and Sanford (unifoliate) during the growing season, except for one sampling time (67 DAS) in 2004 at Saskatoon. In 2005, CDC Yuma had a greater biomass than Sanford over all the sampling times.

At Swift Current, CDC Yuma had a greater biomass accumulation than Sanford from pre-anthesis until early the flowering stage in 2003 and 2004, and during the period from vegetative growth (47 DAS) until the pod filling stage (96 DAS) in 2005. Flowering time in indicated in table 4.1.

In 2003, biomass production at vegetative defoliation decreased in response to defoliation at 38 DAS (Figure 4.2A); however, the difference disappeared after five days of defoliation initiation at Saskatoon. This same treatment caused reduced biomass production from first flower (44 DAS) to post-anthesis (50 DAS) at Swift Current (Figure 4.2B). Biomass declined in flowering defoliation treatment in response to defoliation from 55 DAS, and was maintained until 89 DAS at Saskatoon (Figure 4.2A). However, defoliation at first flower had no effects on

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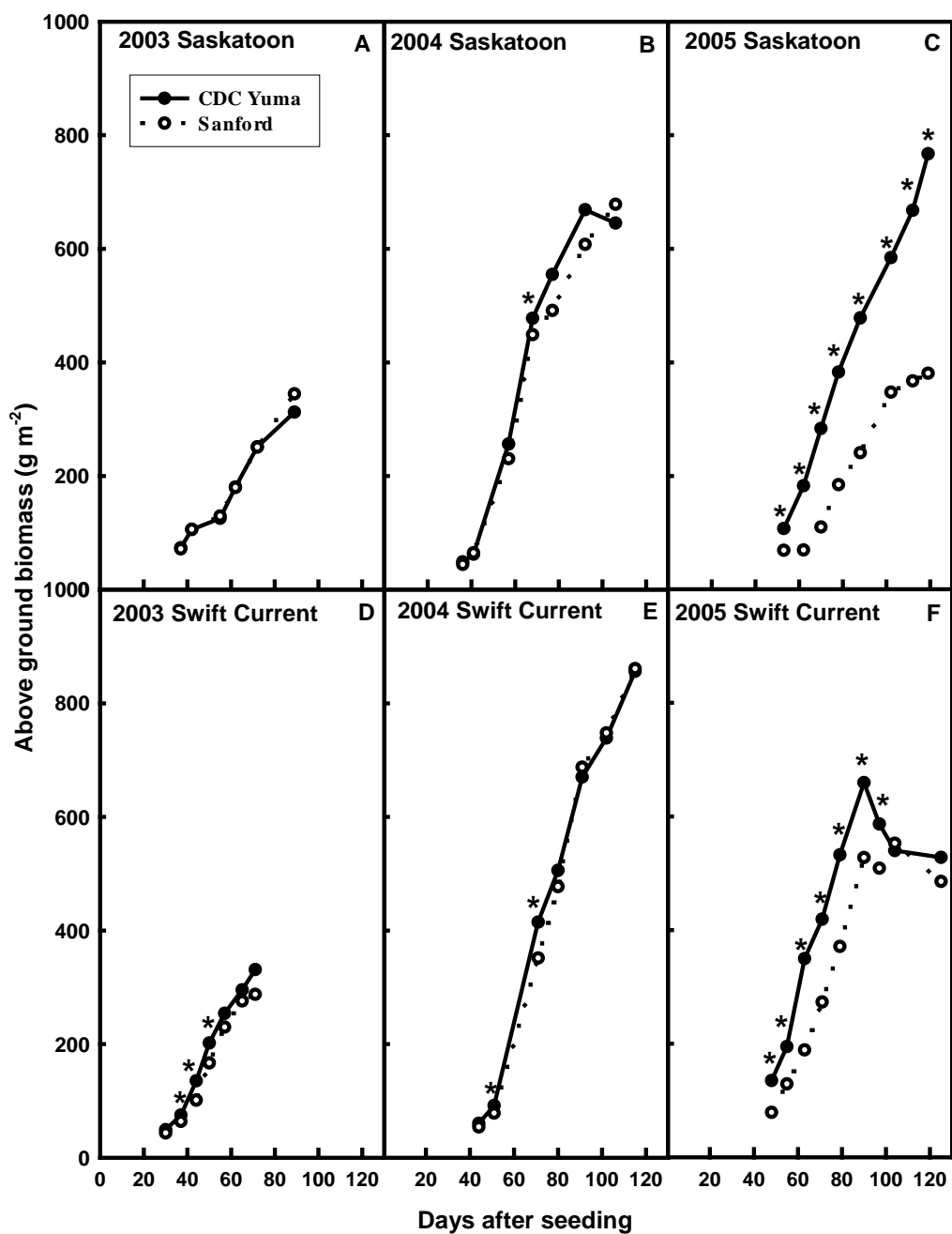
Figure 4.1 Above-ground biomass accumulation as a function of days after seeding in two kabuli chickpea cultivars CDC Yuma (fern-leaf) and Sanford (unifoliate–leaf) in 2003, 2004 and 2005 at Saskatoon and Swift Current. * indicates biomass differed significantly at P<0.05 between the fern and unifoliate leaf types at a given sampling date.
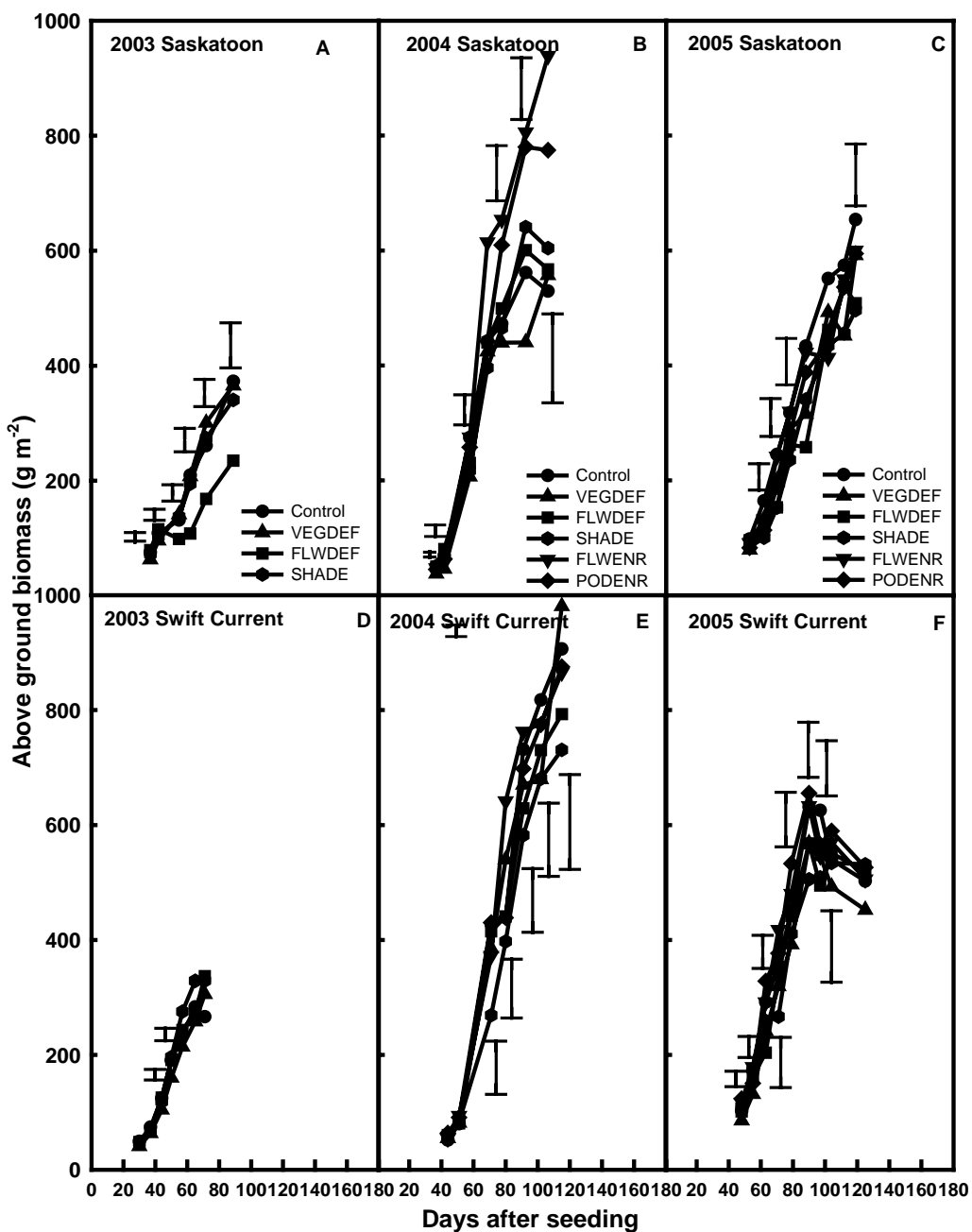
Figure 4.2 Above-ground biomass accumulation as a function of days after seeding for different canopy treatments: control (CK), defoliations at vegetative stage (VEGDEF) and first flower stage (FLWDEF), shading from vegetative stage to first flower stage (SHADE), light enrichments initiated at first flower stage (FLWENR) and pod formation stage (PODENR) averaged across two kabuli chickpea cultivars CDC Yuma and Sanford in 2003, 2004 and 2005 at Saskatoon and Swift Current; vertical bars indicate LSD at 0.05 level at a given sampling date.

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biomass accumulation at Swift Current (Figure 4.2B). There was no difference in biomass production between shading and control treatment in 2003 at both locations.

In 2004 at Saskatoon, defoliation at the vegetative stage resulted in a reduction in biomass production from treatment initiation until the first flower stage (57 DAS), then had a similar biomass production to the control, and then was reduced during the pod-filling stage (92 DAS)(Figure 4.2C). Interesting, defoliation at first flower had no effect on biomass accumulation during the whole growing season at Saskatoon (Figure 4.2C). The shading effect on biomass production was only found at the end of the shade treatment when shade cloth was removed from plots (57 DAS). The significant increase in biomass in response to light enrichment was observed in both treatments starting from the treatment initiation until the last sampling time (106 DAS). Moreover, the largest increase was found in the earlier treatment to be enriched at the first flower stage, compared to enrichment at the pod-formation stage. Thus, the earlier the light enrichment was imposed, the greater the level of biomass accumulation in chickpea.

In 2004 at Swift Current, defoliation at first flower produced greater biomass than the control at 80 DAS and less biomass than the control at 102 DAS (Figure 4.2D). Defoliation at first flower produced less biomass than the control at 71 DAS and between 91 DAS and 119 DAS. The difference in biomass production between shading and the control only became evident around 91 DAS. The light enrichment commencing at first flower produced a higher biomass than enrichment at pod filling (80 DAS) and maintained higher biomass at 91 DAS, although this treatment

was not statistically different with the control. The effect of light enrichment at pod formation on biomass production was not significant.

In 2005 at Saskatoon, the vegetative defoliation did not differ in biomass production compared to the control treatment (Figure 4.2E). Biomass production of the defoliation treated at first flower was decreased between 70 DAS and 119 DAS. The shade treatment had significantly less biomass production between flowering (62 DAS), pod filling (78 DAS) and the final sampling date (119 DAS). Both light enrichment treatments had almost no effect on biomass accumulation at both Saskatoon and Swift Current.

In 2005 at Swift Current, vegetative defoliation had a lower biomass only immediately after the defoliation between 47 DAS and 62 DAS (Figure 4.2F). Similarly, defoliation at first flower reduced biomass immediately after defoliation (62 DAS), but the difference disappeared and then reappeared again at pod filling (96 DAS). Shade reduced biomass over the control at three sampling times, 70 DAS, 87 DAS and 96 DAS, respectively. Both light enrichment treatments had almost no effect on biomass accumulation.

There were no significant cultivar × treatment interactions for maximum biomass in all the six location-years (Appendix 15). There were no significant differences between the two leaf types in 2003 and 2004 for maximum biomass (Table 4.6). In 2005, CDC Yuma had a greater maximum biomass compared with Sanford. The vegetative defoliation treatment had similar maximum biomass to the control treatment in five out of six location-years, but a lower biomass at Swift Current in 2005. Defoliation at first flower resulted in less maximum biomass

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Table 4.6 Comparisons of maximum biomass (g m^{-2}) between Sanford and CDC Yuma and six canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment Factors		**Maximum Biomass (g m^{-2})**					
	Year	**2003**		**2004**		**2005**	
Cultivars	Location	Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
	Sanford (Unifoliate)	348	320	720	921	423	649
	CDC Yuma (Fern)	318	348	724	894	777	694
	LSD (0.05)	NS	NS	NS	NS	61	43
Treatments							
	Control	385	309	615	957	659	706
	VEGDEF	355	315	596	981	604	631
	SHADE	241	346	635	829	556	631
	FLWDEF	351	364	675	805	564	668
	FLWENR	NA	NA	967	920	608	683
	PODENR	NA	NA	844	953	611	710
	LSD (0.05)	76	NS	118	130	NS	75

NA indicates FLWENR and PODENR treatments are not available.

NS indicates no significant differences at P ≤ 0.05.

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

compared to the control at Swift Current in 2004; otherwise biomass was the same as the control. Shading reduced maximum biomass at Saskatoon in 2003 and Swift Current 2005 compared to the control; otherwise the shade treatment was the same as the control. Light enrichment commencing at both first flower and pod formation increased maximum biomass compared to the control in Saskatoon 2004, and the extent of the increase was highest at first flower. Likely, light enrichment during pod formation was too late for significant practical impact. In 2005, light enrichment at flowering and pod formation did not increase biomass compared to the control.

4.3.5 Crop growth rate

There were no significant cultivar × treatment interactions for crop growth rate at all the dates in the six location-years (Appendix 16). CDC Yuma (fern-leaf) had a similar CGR to Sanford (unifoliate leaf) in 2003 at Saskatoon (Figure 4.3A). However, at Swift Current between 43 DAS and 50 DAS, CDC Yuma had a higher CGR than Sanford (Figure 4.3B). CDC Yuma and Sanford had a similar CGR in 2004 at both locations (Figure 4.3C and D). In 2005 at Saskatoon, the CGR for CDC Yuma was higher until anthesis (70 DAS) and higher again at 119 DAS (Figure 4.3E). At Swift Current, around anthesis (63 DAS), CGR was again higher for CDC Yuma (Figure 4.3F).

In 2003 at Saskatoon, CGR was increased in response to the defoliation at vegetative stage (Table 4.7). Throughout the early reproductive period (55 to 62 DAS) period, CGR for defoliation at first flower was significantly less than the control, but similar 10 days after that period. Shading did not change CGR
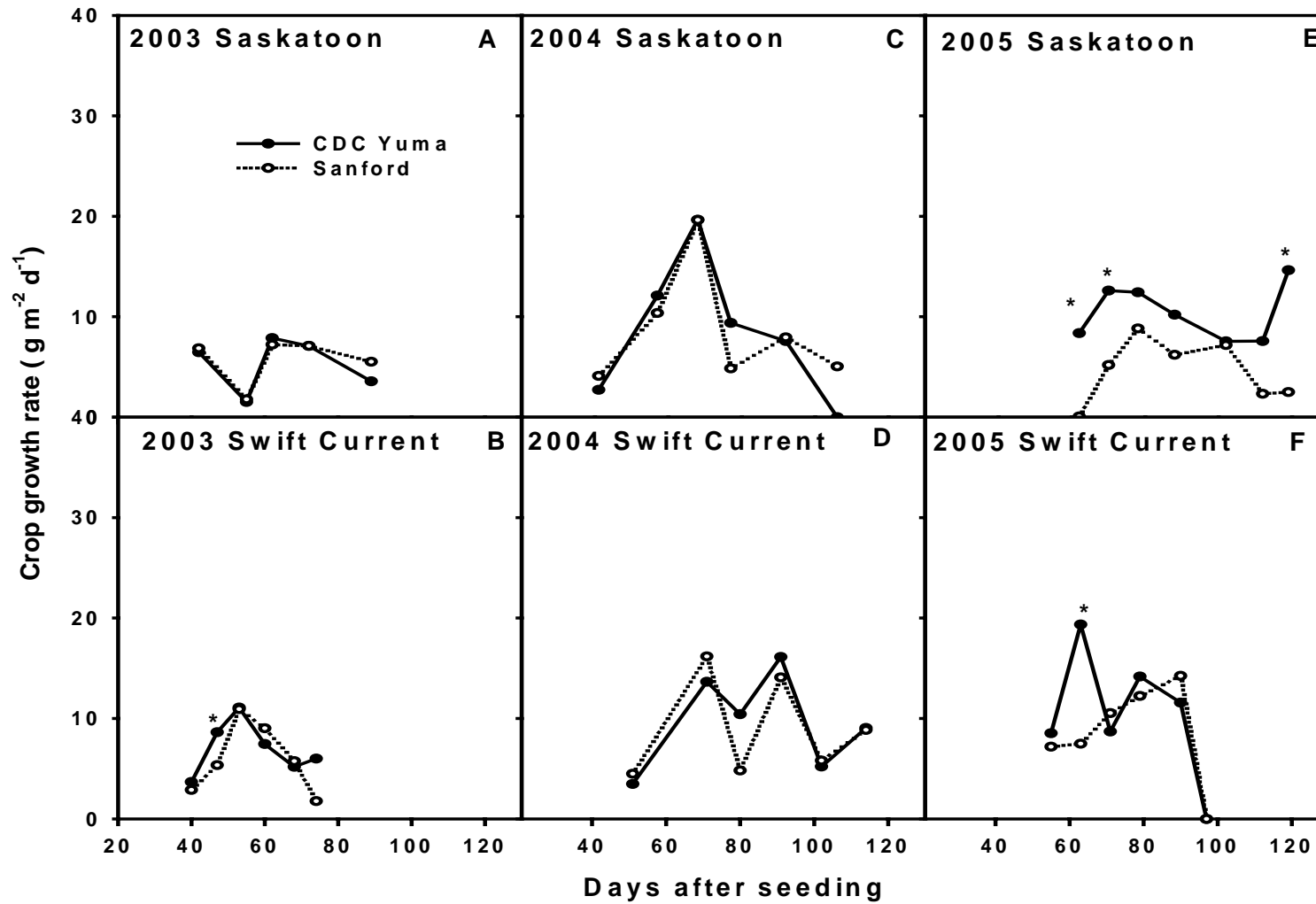
Figure 4.3 Crop growth rate in g m^{-2} per day of two kabuli chickpea cultivars CDC Yuma (fern-leaf) and Sanford (unifoliate-leaf) in 2003, 2004 and 2005 at Saskatoon and Swift Current; vertical bars indicate LSD at 0.05 level. * indicates crop growth rate differed significantly at P<0.05 between the fern and unifoliate leaf types.

Table 4.7 Comparisons of crop growth rate among six canopy treatments at representative sampling dates in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment	Crop growth rate ($g\ m^{-2}\ d^{-1}$)						
	2003						
	Saskatoon			Swift Current			
	DAS 42	DAS 55	DAS 62	Individual sampling dates ξ			
Control	18.7	5.4	42.1	NS			
VEGDEF	24.7	11.8	NS	NS			
SHADE	20.2	NS	NS	NS			
FLWDEF	23.8	-4.3	4.5	NS			
LSD (0.05)	NS	6.0	18.8	NS			
	2004						
	Saskatoon				Swift Current		
	DAS 41	DAS 57	DAS 68	DAS 77	DAS 51	DAS 71	DAS 91
Control	3.7	12.9	15.3	3.4	4.1	17.4	27.8
VEGDEF	1.8	NS	NS	NS	3.9	15.2	11.9
SHADE	3.4	9.4	NS	NS	3.6	9.3	NS
FLWDEF	6.1	9.4	NS	NS	2.9	16.7	NS
FLWENR	NS	13.6	30.9	NS	5.6	13.9	8.2
PODENR	NS	NS	16.8	18.6	3.9	17.0	8.9
LSD (0.05)	NS	3.4	9.0	13.6	NS	4.9	12.9
	2005						
	Saskatoon			Swift Current			
	DAS 62			DAS 55	DAS 63		
Control	7.4			10.1	14.8		
VEGDEF	NS			NS	NS		
SHADE	1.9			9.2	10.5		
FLWDEF	2.1			8.6	5.2		
FLWENR	NS			NS	NS		
PODENR	NS			NS	NS		
LSD (0.05)	3.7			NS	9.4		

†NS indicates no significant differences at P ≤ 0.05.

‡VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

ξ Individual sampling dates means all seven sampling dates in 2003 at Swift Current; treatments did not differ from the control for any sampling date.

significantly compared to the control treatment. There was no canopy treatment

effect on CGR at Swift Current in 2003 (Table 4.7).

In 2004 at Saskatoon, at flowering period (57 DAS), the flowering

defoliation and shading treatments had lower CGRs than the control treatment

(Table 4.7). By 68 DAS, CGR for light enrichment initiated at first flower

increased sharply to a peak value and was significantly higher than other treatments.

For the same period, vegetative defoliation also had a higher CGR than the control.

Similarly, the light enrichment treatment at pod formation had the highest CGR by

77 DAS. At Swift Current in 2004, vegetative defoliation had a similar CGR to the

control until pod formation (Figure Table 4.7). By 91 DAS, CGR for vegetative

defoliation decreased to a lower CGR compared to the control. There was no effect

of defoliation on CGR at first flower. By 71 DAS, shading had a lower CGR

compared to the control. At pod formation, both light enrichment treatments had

lower CGRs than the control treatment.

In 2005 at Saskatoon, by 62 DAS, CGRs for vegetative defoliation and

shade were significantly less than the control (Figure 4.4E). Similarly, at Swift

Current, by 63 DAS, CGR for defoliation at first flower was significantly lower than

the control (Figure 4.4F). Shading also had a lower CGR than the control, although

this difference was not significant. Moreover, CGR for the other treatments during

the 2005 growing season at both locations remained similar to the value of the

control treatment.

4.3.6 Light interception over time and maximum light interception

There were no significant cultivar × treatment interactions for light interception at most of the sampling dates in six location-years (Appendix 17). In 2003 at Saskatoon, both cultivars different in leaf morphology had a similar light interception over the growing season (Figure 4.4A). However, at Swift Current, light intercepted by CDC Yuma was greater than Sanford for the period between early vegetative (28 DAS) and pre-anthesis (37 DAS) (Figure 4.4B). Flowering time is indicated in Table 4.4. In 2004, the fern-leaf cultivar CDC Yuma showed greater light interception between pre-anthesis and anthesis (58 DAS) and pod filling stages (49,58 and 85 DAS) at Saskatoon (Figure 4.4C). However, CDC Yuma had similar light interception as Sanford throughout the growing season except that CDC Yuma achieved greater light interception at 102 DAS at Swift Current (Figure 4.4D). In 2005, CDC Yuma had greater light interception than Sanford throughout the growing season at Saskatoon (Figure 4.4E). At Swift Current in 2005, CDC Yuma maintained higher light interception from the early vegetative stage (55 DAS) until early maturity stage at 104 DAS (Figure 4.4F).

In 2003, treatments which were partially defoliated at vegetative stage intercepted similar amount of light as the control, throughout the growing season at Saskatoon (Figure 4.5A). Defoliation at first flower resulted in decreased light interception for three out of four sampling times after anthesis (57, 79 and 89 DAS, respectively). Of interest, is the shaded canopy had higher light interception compared to the control before anthesis (44 DAS) and this treatment maintained a lower light interception compared to the control during pod filling (79 DAS) at Saskatoon.

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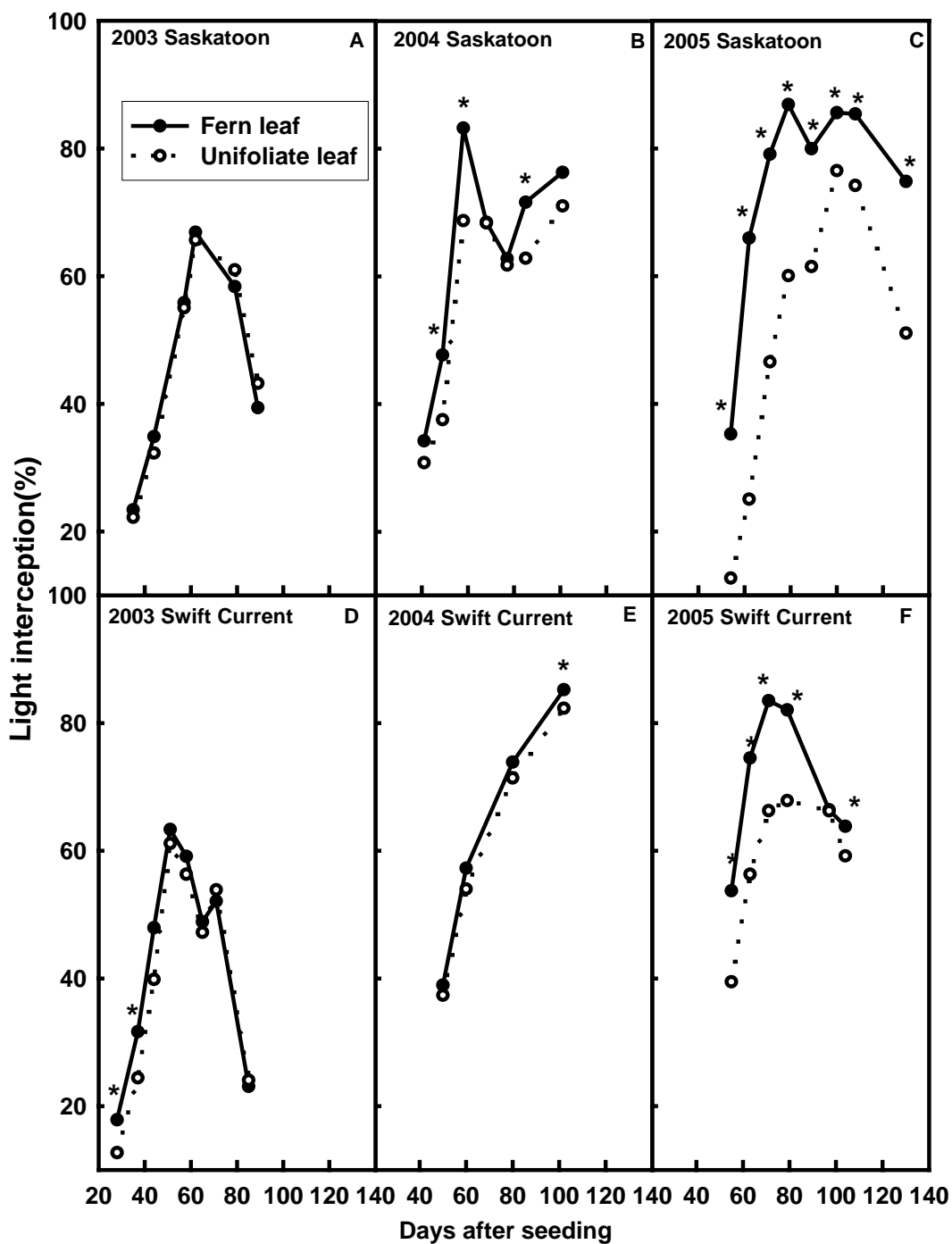
Figure 4.4 Light interception of kabuli chickpea cultivars CDC Yuma (fern-leaf) and Sanford (unifoliate-leaf) grown under different canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current. * indicates light interception differed significantly at P<0.05 between the fern and unifoliate leaf types.

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At Swift Current in 2003 (Figure 4.5B), vegetative defoliation resulted in reduced light interception at either pre-anthesis (37 DAS), flower (51 DAS), or pod-fill (71 to 85 DAS). However, defoliation at first flower had no effect on light interception. Shading resulted in increased light interception between early vegetative (28 DAS) and pre-anthesis (37 DAS) stages, and between flowering (51 DAS) and pod fill (71 DAS).

In 2004 at Saskatoon, light interception in vegetative defoliation declined consistently over the period from 41 to 58 DAS and no other differences were observed afterwards (Figure 4.5C). Light interception decreased after first flower once in response to partial defoliation at first flower. Otherwise, defoliation at first flower did not change light interception during the growing season. Shading caused lower light interception between 49 and 58 DAS with no obvious differences in other sampling stages. No differences were evident between two light enrichment treatments and the control. At Swift Current in 2004, canopy treatments had no effects on light interception except that defoliation at vegetative stage and shading caused reduced light interception before anthesis at 50 DAS (Figure 4.5D).

In 2005, defoliation at the vegetative stage reduced light interception at 71 DAS and 79 DAS at Saskatoon (Figure 4.6E). Light interception for defoliation at the first flower treatment was significantly less than control from 62 DAS until 108 DAS. At Swift Current, light interception decreased significantly in response to partial defoliation at the vegetative stages in 54 DAS (Figure 4.5F). Otherwise, the control and vegetative defoliation showed similar light interception throughout the
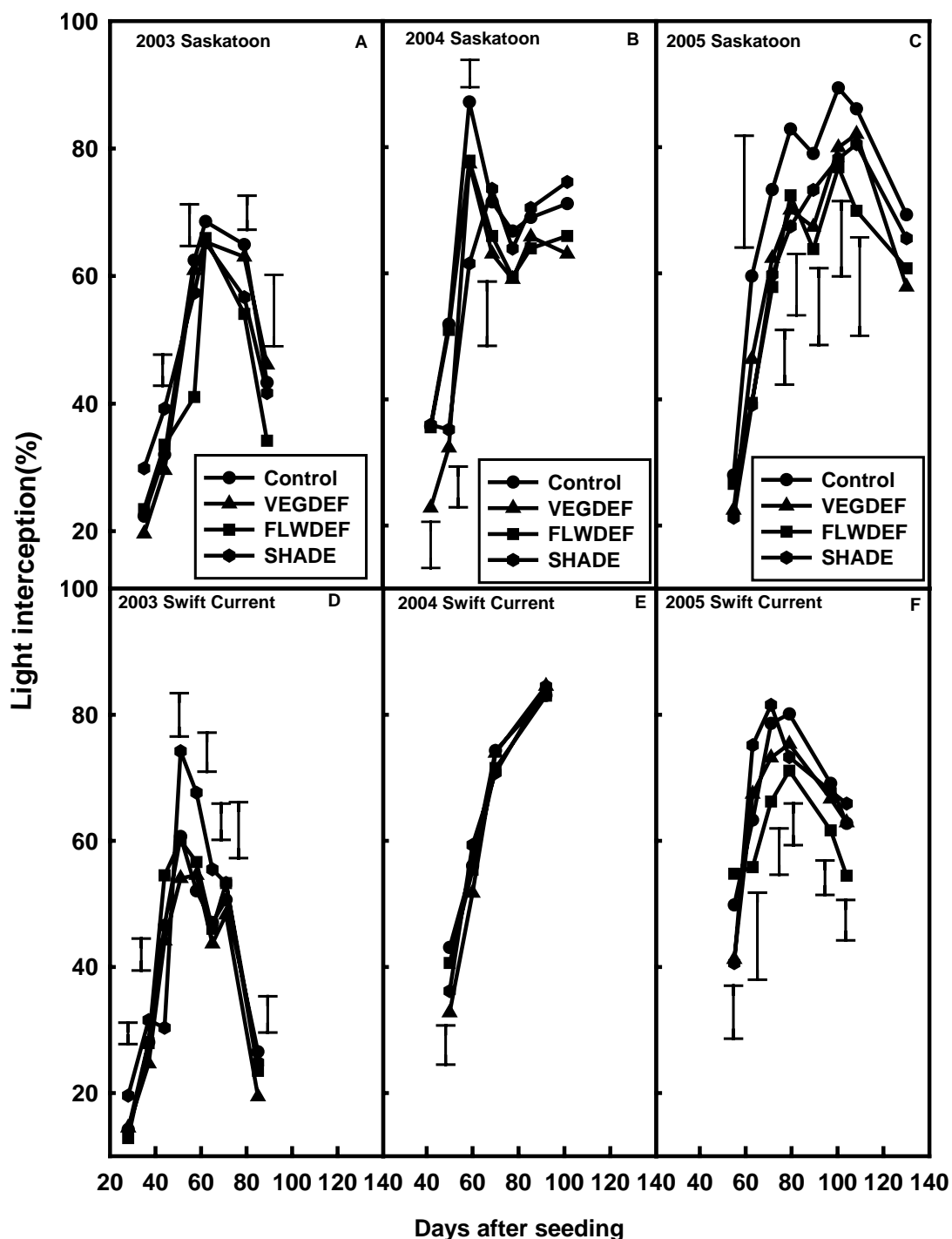
Figure 4.5 Light interception (%) as a function of days after seeding for six canopy treatments: control (CK), defoliations at vegetative stage (VEGDEF) and first flower stage (FLWDEF), shading from vegetative stage to first flower stage (SHADE), light enrichments initiated at first flower stage (FLWENR) and pod formation stage (PODENR) averaged across two kabuli chickpea cultivars: CDC Yuma and Sanford in 2003, 2004 and 2005 at Saskatoon and Swift Current. vertical bars indicate LSD at 0.05 level.

post-anthesis period. The defoliation at first flower resulted in lower light interception compared to the control. This difference was maintained throughout the rest of the growing season at Swift Current. Shading reduced canopy light interception at the sampling intervals 71 DAS, 79 and 100 DAS at Saskatoon; sampling intervals 54 and 78 at Swift Current; otherwise shade treatments had a similar light interception to the control (Figure 4.5F).

There were no significant cultivar × treatment interactions for maximum light interception in all the six location-years (Appendix 18). CDC Yuma, the fern leaf type, had greater maximum light interception than Sanford in four out of six location-years (Table 4.8) with the exception of 2003 when cultivars had the same maximum light interception. No significant change was observed in the vegetative defoliation treatment in 2005 (Table 4.8) because plants were able to compensate. Differences (although not significant) in maximum light interception between the control and the vegetative defoliation treatment were found at Swift Current 2003 and Saskatoon 2004. In 2005, defoliation initiated at first flower had a lower maximum light interception compared to the control, meaning that the defoliated canopy was unable to compensate back to the control level. Shading resulted in lower maximum light interception in 2003 at both locations and Saskatoon (2004). Otherwise, shading had little effect on maximum light interception.

4.3.7 Cumulative intercepted radiation

There were no significant cultivar × treatment interactions for cumulative intercepted radiation at all the sampling dates in any of the six location-years (Appendix 19). In 2003 at both locations, cumulative intercepted radiation did not

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Table 4.8 Comparisons of light interception (%) between Sanford and CDC Yuma and six canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment Factors		**Maximum Light Interception (%)**					
	Year	**2003**		**2004**		**2005**	
Cultivars	Location	Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
	Sanford (Unifoliate)	70	68	78	82	80	74
	CDC Yuma (Fern)	69	71	86	85	91	87
	LSD (0.05)	NS	NS	4	2	5	4
Treatments							
	Control	71	80	88	83	91	84
	VEGDEF	68	62	83	85	85	81
	SHADE	66	70	78	84	85	84
	FLWDEF	73	65	80	83	81	74
	LSD (0.05)	6	8	5	NS	8	5

NA indicates FLWENR and PODENR treatments are not available.

NS indicates no significant differences at P ≤ 0.05.

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

differ between canopy treatments (Figure 4.6A and B; Figure 4.7A and B). In 2004, CDC Yuma (fern-leaf) had a greater cumulative intercepted radiation from 56 DAS until physiological maturity at Saskatoon (Figure 4.6C) and similar cumulative intercepted radiation as Sanford at Swift Current (Figure 4.6D). Similarly, in 2005, CDC Yuma had high levels of cumulated intercepted radiation from flower (62 DAS) until plant physiological maturity in Saskatoon (Figure 4.6E) as well as from pod formation (72 DAS) until plant physiological maturity in Swift Current (Figure 4.6F). In 2004 at Saskatoon, by 42 DAS, both defoliation treatments resulted in lower cumulative intercepted radiation compared to the other treatments and this difference was maintained until the end of the growing season (Figure 4.7C). By 57 DAS when the shade cloths were removed from plots, the cumulative intercepted radiation in the shade treatment remained lower than the control, and this difference was maintained to the end of the season. Similarly, at Swift Current, by 45 DAS, vegetative defoliation and shade treatments had a lower cumulative intercepted radiation than the control treatment and remained to physiological maturity (Figure 4.7D). Shading caused lower cumulative intercepted radiation from 60 DAS until physiological maturity.

In 2005 at Saskatoon, a lower cumulative intercepted radiation was observed in the defoliation treatment at first flower from 79 DAS to physiological maturity, about 145 DAS (Figure 4.7E). Cumulative intercepted radiation differed in the shade treatment compared to the control from 62 DAS to pod filling stage at 89 DAS. At Swift Current (Figure 4.7F), shading significantly lowered cumulative intercepted radiation
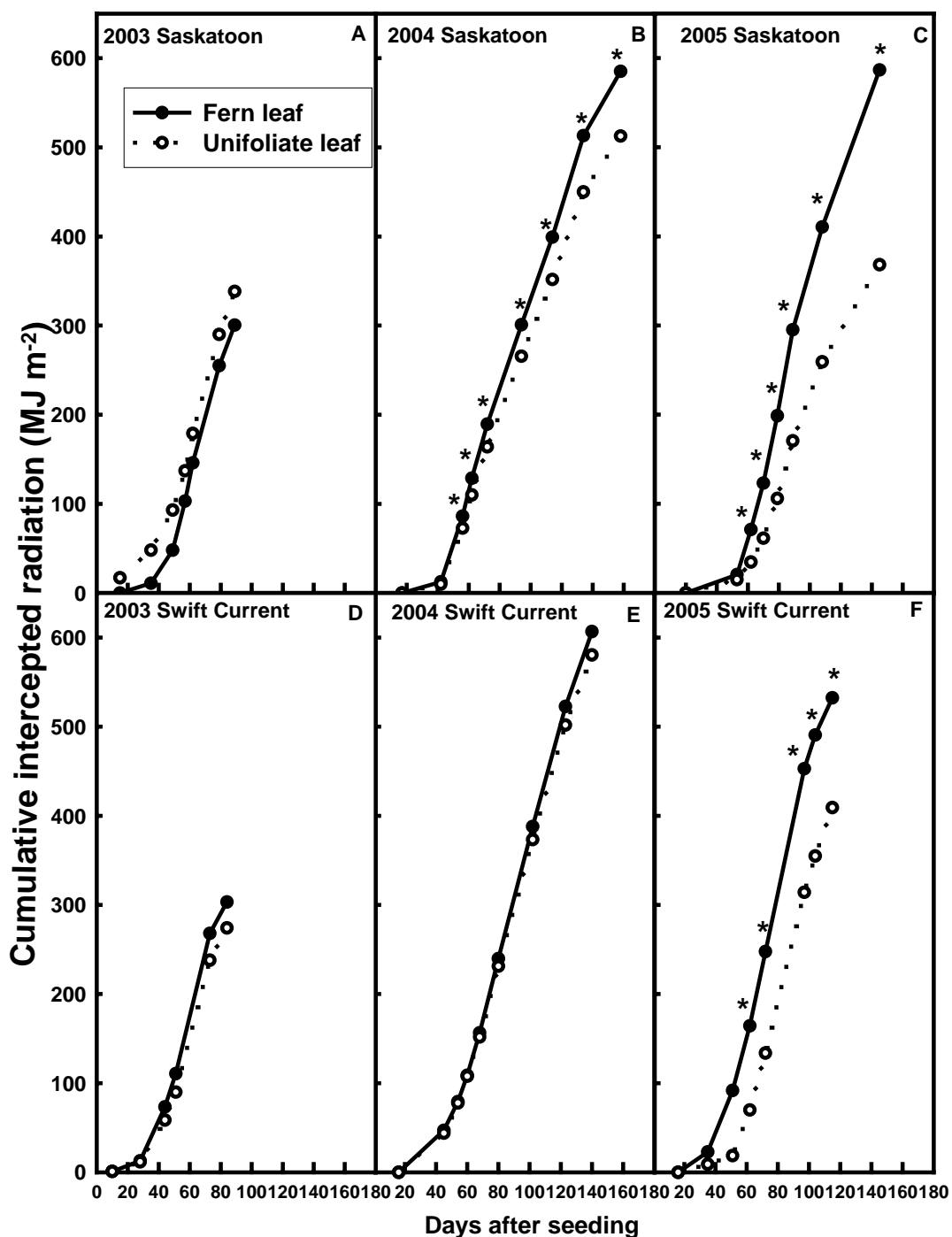
Figure 4.6 Cumulative intercepted radiation (MJ m^{-2}) of kabuli chickpea cultivars CDC Yuma (fern leaf) and Sanford (unifoliate) grown under different canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current. * indicates cumulative intercepted radiation differed significantly at P<0.05 between the fern and unifoliate leaf types.

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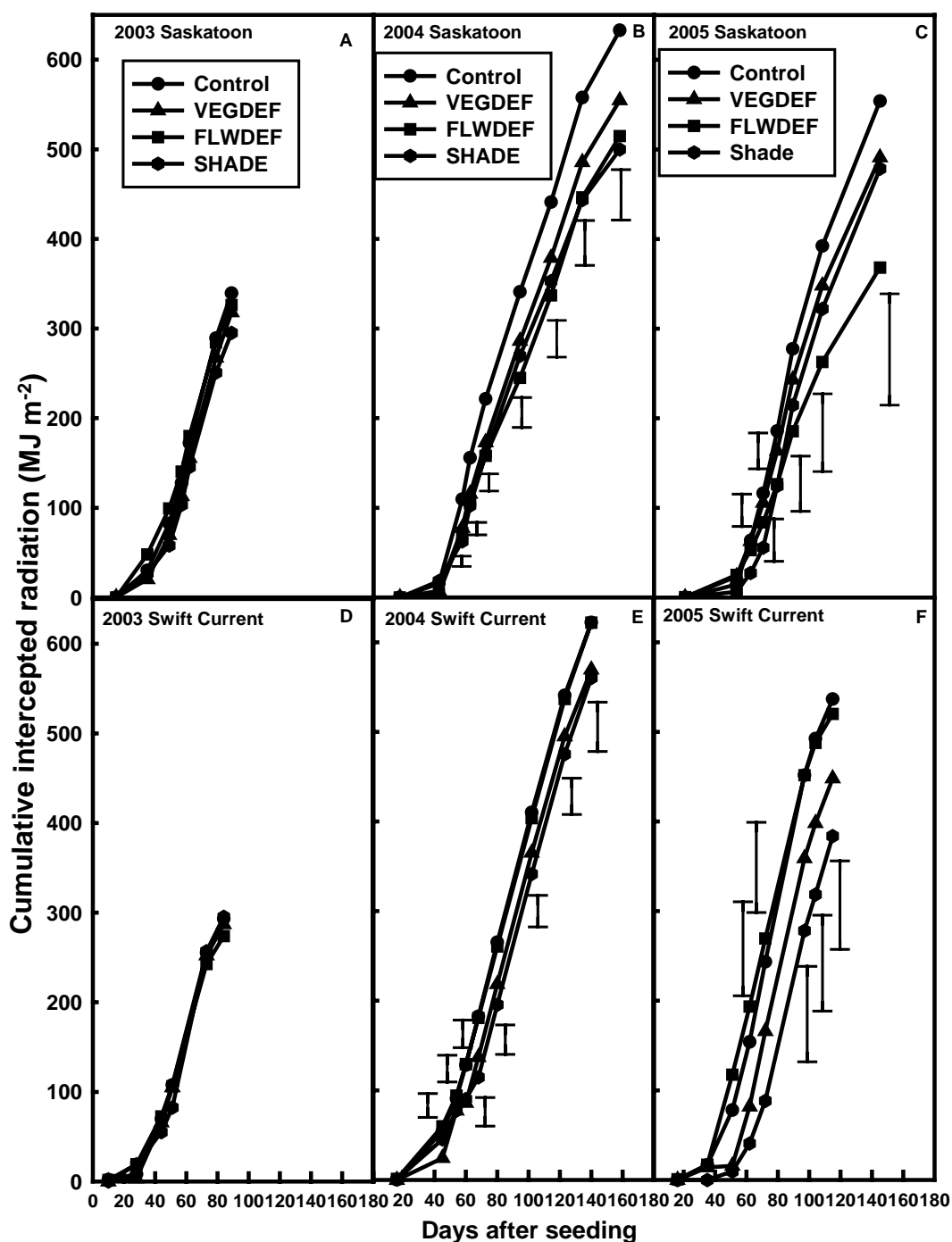
Figure 4.7 Cumulative intercepted radiation (MJ m^{-2}) as a function of days after seeding for the different canopy treatments: control (CK), defoliations at vegetative stage (VEGDEF) and first flower stage (FLWDEF), shading from vegetative stage to first flower stage (SHADE), light enrichments initiated at first flower stage (FLWENR) and pod formation stage (PODENR) averaged across two kabuli chickpea cultivars CDC Yuma and Sanford in 2003, 2004 and 2005 at Saskatoon and Swift Current; vertical bars indicate LSD at 0.05 level.

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compared to the control from 62 DAS (ten days after the shade treatment was imposed), until the end of the growing season (115 DAS).

There were no significant cultivar × treatment interactions for seasonal cumulative intercepted radiation in all the six location-years (Appendix 20). The fern leaf cultivar CDC Yuma intercepted more incoming solar radiation than the unifoliate cultivar Sanford in four out of six location-years (Figure 4.6 and Table 4.9). In 2003, no differences among any of the treatments were observed, likely due to severe drought that ended growth early in this season, and final cumulative radiation was lower than in other years. Seasonal cumulative intercepted radiation in the vegetative defoliation treatment was less than the control in Saskatoon 2004 and Swift Current 2005. The treatment of defoliation at first flower cumulated less radiation than the control at both locations in 2004 and at Swift Current in 2005. Intercepted radiation was significantly reduced under the shade treatment compared to the control in 2004 at both locations and at Swift Current in 2005.

4.3.8 Harvest index and yield

There were no significant cultivar × treatment interactions for harvest index in all the six location-years (Appendix 12). Fern-leaf CDC Yuma had a higher HI than Sanford in four out of six location-years, implying that fern-leaf cultivars may allocate a higher proportion of biomass to final yield (Table 4.10). Harvest index was reduced under both defoliation treatments at Swift Current in 2003, but remained similar to the control due to drought in Saskatoon 2003, and in 2004 and 2005. Harvest index was significantly lower in the shade treatment compared to the control in three out of six location-years. Therefore, adequate assimilatory capacity

Table 4.9 Comparisons of seasonal cumulative intercepted radiation between Sanford and CDC Yuma and six different canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment Factors		Seasonal Cumulative Intercepted Radiation (MJ m^{-2})					
	Year	**2003**		**2004**		**2005**	
Cultivars	Location	Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
	Sanford (Unifoliate)	338	280	513	580	373	414
	CDC Yuma (Fern)	300	300	585	607	587	538
	LSD (0.05)	NS	NS	40	39	87	70
Treatments							
	Control	339	285	633	622	554	556
	VEGDEF	318	271	555	569	491	448
	FLWDEF	327	291	515	622	401	384
	SHADE	295	311	500	560	471	520
	LSD (0.05)	NS	39	56	NS	124	90

NA indicates FLWENR and PODENR treatments are not available.

NS indicates no significant differences at P ≤ 0.05.

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

Table 4.10 Comparisons of harvest index for Sanford and CDC Yuma and six different canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment Factors		Harvest Index					
	Year	2003		2004		2005	
Cultivars	Location	Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
	Sanford (Unifoliate)	0.35	0.32	0.27	0.28	0.09	0.31
	CDC Yuma (Fern)	0.33	0.38	0.39	0.30	0.39	0.37
	LSD (0.05)	NS	0.02	0.05	NS	0.04	0.03
Treatments							
	Control	0.35	0.38	0.34	0.31	0.23	0.35
	VEGDEF	0.35	0.35	0.30	0.33	0.26	0.37
	SHADE	0.34	0.33	0.28	0.20	0.17	0.28
	FLWDEF	0.32	0.34	0.35	0.26	0.26	0.34
	FLWENR	NA	NA	0.35	0.30	0.26	0.36
	PODENR	NA	NA	0.36	0.34	0.27	0.36
	LSD (0.05)	NS	0.03	0.08	0.06	0.05	0.05

NA indicates FLWENR and PODENR treatments are not available.

NS indicates no significant differences at $P \leq 0.05$.

VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.

during the period from vegetative to first flower stages were important to maintain HI. Light enrichment treatments at both flowering and pod formation stages did not change HI significantly compared to the control at four location-years. The most sensitive growth stage associated with HI was late vegetative and flowering, which corresponds to the establishment of the first reproductive organs.

Drought stress reduced yield for 2003 compared with 2004 and 2005. There were no significant cultivar × treatment interactions for yield in all the six location-years (Appendix 22). CDC Yuma had greater yield than Sanford in four out of six location-years. Defoliation treatments imposed at vegetative and first flower stages did not significantly alter yield in all location-years (Table 4.11). The shade treatment reduced yield by 40%, 25%, and 47% at Saskatoon in 2003, 2004 and 2005 and by 50% and 26% at Swift Current in 2004 and 2005, respectively. There was no shade effect on yield in Swift Current 2003.

Light enrichment initiated at first flower increased yield in Saskatoon (2004 and 2005), compared to the control, suggesting that first flower is an important stage for determining yield in kabuli chickpea. Moreover, no significant impact was seen at Swift Current. However, light enrichment during the pod formation stage did not increase yield significantly at all four location-years. A gradual decline in solar radiation over summer months during the pod formation stages is likely the reason for similar yields in the enrichment treatments compared to the control.

4.4 Discussion

4.4.1 Temperature and water stress effects

Dry weather conditions in 2003 at both locations produced smaller leaf areas

Table 4.11 Comparisons of yield between Sanford and CDC Yuma and six different canopy treatments in 2003, 2004 and 2005 at Saskatoon and Swift Current.

Treatment Factors		Yield (Kg ha^{-1})					
	Year	2003		2004		2005	
Cultivars	Location	Saskatoon	Swift Current	Saskatoon	Swift Current	Saskatoon	Swift Current
	Sanford (Unifoliate)	809	752	903	1979	159	1400
	CDC Yuma (Fern)	914	715	1360	2115	2590	1958
	LSD (0.05)	NS	NS	162	NS	1119	267
Treatments							
	Control	955	725	1121	2188	2146[†]	1724
	VEGDEF	968	662	838	2217	2334	1738
	SHADE	682	737	899	1101	1246	1371
	FLWDEF	840	810	1169	1830	2981	1573
	FLWENR	NA	NA	1461	2432	5216	1663
	PODENR	NA	NA	1294	2515	1615	2004
	LSD (0.05)	203	NS	281	425	2801	462

NA indicates FLWENR and PODENR treatments are not available.
NS indicates no significant differences at P ≤ 0.05.
VEGDEF, FLWDEF, SHADE, FLWENR, PODENR represent half defoliation at vegetative and first flowering stage, 45% shading during vegetative till first flower and light enrichment during first flower and the pod formation stage, respectively.
[†] CDC Yuma only under treatment column.

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and lower light interception and consequently resulted in lower yield due to drought and water stress compared to 2004 and 2005. This corresponded to the observation of Singh (1991) who reported that water deficits prior to flowering decreased canopy development, light interception and dry matter production to the maximum extent. High temperature significantly decreased the CGRs in 2003 compared to 2004 and 2005, also seen by Singh et al., (1982) in a study conducted at indian subcontinent environmental. Assimilate availability affects node appearance and leaf production (Stutzel and Aufhammer, 1991). Water stress in 2003 limited assimilate availability for leaf growth. Moreover, temperatures above 22 $^{\circ}$C resulted in a lower node appearance rate (Soltani et al., 2006) and data in this thesis show lower plant height compared to the corresponding heights in 2004 and 2005. Singh (1991) found that water stress during all growth phases, especially after flowering, increased the allocation of assimilate partitioned to pods and seeds. This finding was also seen in the relatively higher HI in 2003 compared to 2004 and 2005.

4.4.2 Leaf morphology effects

CDC Yuma had higher maximum biomass and light interception, cumulative intercepted radiation, and HI in four out of six location-years. Besides these, CDC Yuma had a higher CGR around anthesis and greater yield in three out of six location-years.

Leaf area is a major variable affecting the ability of the plant to gain carbon (Holman and Oosterhuis, 1999). Furthermore, the major source of carbohydrates for the developing seed in chickpea is the subtending leaves of pods (Singh and

Pandey, 1980). The advantage of the fern leaf canopy in source and sink manipulation was likely due to it having a larger subtending leaf area for each pod compared to the unifoliate leaf canopy. Biomass accumulation is determined primarily by the product of net assimilation rate and assimilatory surface, which is mainly leaf area. Thus the differences in biomass accumulation could also be due to leaf area (Mythili and Nair, 1996). The higher maximum light interception and accumulated intercepted radiation of the fern leaf canopy was most likely due to a faster and larger leaf area development in the short growing season. The higher CGRs around anthesis could be explained as a higher canopy assimilatory ability during this period. All of the above explained the superior performance of the fern-leaf canopy compared with the unifoliate one.

4.4.3 Defoliation effects

Both defoliation treatments when compared to the control treatment resulted in less maximum biomass in one out of six location-years, less HI in one out of six years, less maximum light interception in three out of six location-years and less cumulative intercepted radiation in two out of six location-years. Together, these responses were minor and defoliation at the vegetative period and first flower had no effect on yield in all location-years.

The lack of a significant defoliation effect on yield may be largely due to leaf regrowth potential before and around anthesis. These results were consistent with Board et al. (1994) and Weber (1955) on soybean. In contrast, Pandey (1984) reported that yield and dry matter production decreased significantly in chickpea in response to 50% defoliation undertaken 60 days after seeding in a subtropical

environment. The author also found that the most sensitive stages to 50% defoliation were the pod formation and seed filling stages. Defoliation before pod formation permitted new leaf production which can provide assimilate support needed for any later formed pods. Sheldrake and coworkers (1978) found that 25, 50, or 75% of defoliation from first flower and maintained to plant maturity reduced yield significantly, and caused chickpea to lose the ability to compensate for lost leaf area. Single versus sequential defoliation may explain this inconsistency because the plots in this thesis had a single defoliation only. In a previous study by Pandy (1984), chickpea showed a strong compensatory ability. For example, it compensated for the loss of all flowers and young pods for up to two weeks after flowering (Pandey, 1984). In the present study, chickpea under defoliation treatments had the ability and sufficient time to replace leaves and compensate for 'lost' metabolites from removed leaves, and to translate assimilate to later formed pods and seeds. As a result, yields were similar to the control treatment.

The impact of defoliation at the vegetative and first flower periods on different physiological parameters can be explained below. Firstly, high temperature and drought stress in July and August in 2003 at Swift Current (Table 4.3) may have contributed to the lack of compensatory response by the defoliation treatments and resulted in lower HI and maximum light interception. Secondly, adequate moisture is a prerequisite to recovery from defoliation seen in soybean by Smith and Bass (1972). In 2004 at Saskatoon, adequate moisture allowed leaf replacement after defoliation, resulting in seed productions similar to the control, although both defoliation treatments had a lower cumulative intercepted radiation.

Thirdly, an increase in the assimilate supply from remaining leaves is possible (Wareing et al., 1968). Klubertanz et al. (1996) also reported that compensatory growth observed in their defoliation treatments resulted in more leaves in the defoliated treatment than expected. The thesis results were similar in that carbohydrates were partitioned to leaves remaining at the plant, resulting in larger leaves and a significantly higher maximum light interception than the control at Swift Current 2004 (Table 4.8). Finally, in 2005 at Saskatoon, although defoliation at first flower had lower maximum light interception and cumulative intercepted radiation (Table 4.8 and 4.9), it still had a similar maximum biomass and HI, and consequently a similar yield to the control treatment.

4.4.4 Shading effects

Plant height was increased in the shade treatment in this study. Increased plant height under reduced light environment has also been reported in chickpea and cassava (*Manihot esculenta Crantz*) (Miah et al., 2003; Okoli and Wilson, 1986; Fukai et al., 1984). Ephrath and coworkers (1993) also found that shading resulted in lengthening of internodes and increased lodging in soybean. Height increase may be due to lower light induced etiolation, or even assimilate redistribution to the shoot (Fukai et al., 1984).

Yield reduction due to shading was related to a decrease in HI in 2004 at Swift Current, a decrease in both biomass and HI in 2005, or a decrease in maximum biomass in 2003 at Saskatoon. Crop growth rate for the shade treatment was significantly reduced around anthesis in 2004 and 2005 at both locations but had no effect in 2003, which indicated that shading can temporarily reduce canopy

assimilatory capacity, and compensatory growth can bring the canopy assimilatory capacity back to that of the control. Shading decreased assimilate availability by limiting assimilate production, producing less maximum biomass in three out of six location-years, and decreased the partitioning of biomass to reproductive organs (Table 4.10), which was similar to results previously reported in chickpea (Verghis et al., 1999).

Light interception was temporarily reduced by the shade treatment around anthesis and regained similar light interception to the control in 2004 (Figure 4.6C and D), or after pod formation in 2003 at Saskatoon and 2005 at both locations (Figure 4.6A, E and F). Board and coworkers (1992b) found that light interception of soybean crops during vegetative and early reproductive stages was more critical for determining the yield in narrow rows compared with later stages of growth. In this thesis, light interception reduction after the pod formation stage seemed to be related to the reduction in yield in three location-years (2003 Saskatoon, 2005 at both locations). Reduction in light interception around anthesis did not necessary translate to yield reduction in chickpea.

Interestingly, shading caused higher light interception before anthesis in 2003 at both locations and from flowering until pod filling at Swift Current in 2003, findings which were unexpected and contradicted results from 2004 and 2005. Most likely shading reduced air temperature in an oppressive hot year, thereby improving physiological processes. The peak rate of photosynthesis was recorded at 22°C air temperature during flowering and the pod development stages for chickpea grown in India, and a depression of net photosynthesis was found at higher air

temperatures (Singh et al., 1982). In 2003 at both locations, around June 18th and June 19th, the temperature reached 35 ^{o}C. Chickpea under 50% shade cloth had more favorable conditions during the excessively hot days around solar noon because soil and air temperature, wind speed and water use in soil, can all be reduced (Allen, 1975).

Alternatively, chickpea yield reduction can be explained in terms of cumulative intercepted radiation. Miah et al. (2003), indicated that 84% of chickpea yield could be attributed to PAR. Chickpea under the shade treatment in this thesis accumulated less intercepted radiation than the control in 2004 at both locations, and in 2005 at Swift Current, for the periods from flowering until physiological maturity. However, there was no yield difference between shade treatment and the control in 2004 at Saskatoon, probably due to an increased RUE under the shade treatment. The RUE of soybean and peanut has been theoretically calculated to increase with a decrease in the level of incident radiation and an increase in the proportion of diffuse radiation (Sinclair et al., 1992; Hammer and Wright, 1994). Radiation use efficiency has even increased when the diffuse component of incident radiation is enhanced under shade shown in two tropical grass species (Healey et al., 1998).

Shading decreased yield by more than 25% in five out of six location-years. Similarly, Verghis et al. (1999) found that shading caused 80% yield reduction, compared to unshaded plants in New Zealand. However, on the Indian subcontinent, 50% shading throughout reproductive stages had no yield-reducing effect by using white cloth (Sheldrake et al., 1978). The shaded chickpea plants had increased

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vegetative growth and delayed leaf senescence, all of which probably resulted from the increased flower and pod abortion of the shaded chickpea and lower pod growth rates (less pod-filling) per plant. Supposedly, insufficient sunlight leads to decreased photosynthetic activity and reduced assimilate. This results in pod abscission (Schou et al., 1978; Egli and Zhen-wen, 1991), reduction in pod and seed numbers per plant in soybean (Mann and Jaworski, 1970; Jiang and Egli, 1993; Kakiuchi and Kobata, 2004), increased fruit abortion in cotton (Pettigrew, 1994); and greater pod abortion and reduced pod filling per plant in chickpea (Verghis, 1999; Miah et al., 2003).

4.4.5 Light enrichment effects

The biomass production in 2004 at Saskatoon and yield in 2004 and 2005 at Saskatoon was increased when light enrichment occurred during the first flower stage and the pod formation stage. However, the degree of light enrichment was greater in the early versus the late reproductive period. These findings concur with findings in soybean that a greater increase in seed yield when light enrichment was initiated at late vegetative compared with early pod formation stage (Mathew et al., 2000). Light enrichment at pod formation occurred when radiation levels were decreasing in mid August and September, compared with July and early August when flowering occurs. Also, canopy photosynthetic activity declines gradually after flowering and during pod development (Kumari and Sinha, 1972; Sinha et al, 1988). Saxena, (1984) and Singh (1991) both showed about 15% -20% of the assimilate produced prior to pod initiation was translocated to pods.

In soybean, Kokubun and Watanabe (1981) altered the light environment of the canopy by keeping upper leaves vertical and increasing the incident illumination on lower leaves. The yield increased when the treatment started at flowering, whereas yield decreased for plants treated from pod formation to maturity. However, the specific reason for this effect was not given. A positive effect on plant alteration was greater in a year with a decrease in the amount of incident solar radiation, and when LAI was maximal (Kokubun and Watanabe, 1981). This observation corresponds to those in this thesis because 2004 was a cold and wet year, with lower solar radiation during the whole growing season, and the light enrichment treatment caused a significant yield response. Flowering and pod development are the most sensitive stages of growth affecting the final grain yield of chickpea (Prasad et al., 1978). Flowering corresponded to when LAI increased rapidly and reached its maximum, causing mutual shading and leaves. The reason for the yield increase at Saskatoon in 2005 was likely due to the canopy having reached about 90% closure during the pod filling stage. The amelioration of light competition in the canopy during this period by light enrichment increased yield.

Yield component data was not available in this study. However, based on a previous publication, the number of pods per plant was the yield component most sensitive to source-sink manipulation (Pandey, 1984). Pod number depended on the number of fruiting sites, for example leaf axes, and the supply of assimilate to these at the pertinent time (Siddique et al., 1984). Post-flowering may have been out of phase with the more slowly developing leaves and associated auxiliary buds (Siddique et al., 1984). The indeterminate chickpea is typically still growing

vegetative organs during pod formation; developing reproductive sinks are competing for assimilate with vegetative sinks and this competition may not permit a significant increase in the number of reproductive sinks.

Both light enrichment treatments caused increased CGRs, probably due to an increased net assimilation rate, as found in soybean (Kokubun and Watanabe, 1981). The CGR is directly related to the amount of radiation intercepted by the crop (Gardner et al., 1985). A higher CGR during flowering and pod formation may allow more pods to be set and thus increase yield. Indeterminate plants have more advanced reproductive development in the lower part of the plants than in the upper part (Fehr et al., 1977). By this reasoning, high levels of available assimilate and light penetration into the lower part of the canopy by light enrichment in this thesis may have contributed to an increase in both the photosynthetic ability of lower leaves and the pod set at lower nodes. In soybean total dry matter increased by increased light penetration into the lower portion of the canopy. This effect was due to an increase in the assimilate distribution to pods during the flowering stages and also to an increase in the carbohydrate reserves, which would have been translocated to the pods at a later stage (Kokubun and Watanabe, 1981). Moreover, light enrichment during early stages of soybean development increased availability of assimilate to developing reproductive structures, increased flowering, and reduced flower and pod abscission (Mathew et al., 2000). All these resulted in higher final pod number at harvest.

5.0 General Discussion

5.1 Best leaf type for short-growing environment in Saskatchewan

In the absence of factors such as nutrient deficiencies, temperature extremes, or water stress, intercepting solar radiation is the major limitation to plant development and growth (Hussein, 1999). Increasing plant populations has been previously used as a management method in improving solar radiation interception by chickpea canopies, leading to increased yield (Leach and Beech, 1988; Ayaz et al., 2004). This is particularly important in Saskatchewan, where the growing season is short. The development and continuing introduction of cultivars with greater short-season yield potential has been an important priority for chickpea breeders in Canada. Among these developments are new chickpea cultivars differing in canopy architecture and leaf morphology. Thus, manipulating plant population and the use of chickpea cultivars with the best canopy architecture will enable efficient use of the available solar radiation during a short growing season.

Canopy architecture is a function of leaf number, shape, distribution, orientation and plant size, as seen in the example of corn (Williams et al., 1968). Canopy light interception and photosynthesis are closely related to leaf area index and crop yield. Moreover, leaf area index and canopy structure are influenced by leaf angle, leaf area per plant and plant density (Monteith and Elston, 1983; Modarres et al., 1997). In this thesis, chickpea cultivars with the fern leaf trait had

more leaf area per plant, a larger leaf size and consequently a higher leaf area index than their unifoliate counterparts (Chapter 3 and Chapter 4). These characteristics allow them to intercept more light and produce more photosynthate during the short-growing season in Saskatchewan. The fern leaf cultivars produced larger individual leaves for each subtending pod, which is the most important part of the plant canopy in terms of the contribution of assimilate to the seed. Therefore, the fern leaf increased canopy closure, had a higher maximum light interception, and higher cumulative intercepted radiation and yield (Chapter 3 and Chapter 4). Large leaf size is a trait used to increase canopy closure (Hunter. 1980; Well et al., 1993; Heitholt et al. 2005).

In addition, the fern-leaf cultivars used in this thesis had a relatively upright leaf orientation compared to the unifoliate orientation on a visual basis. Erect leaf orientation is advantageous for the interception of solar radiation, minimizing mutual shading at high plant population densities. The fern-leaf cultivars shaded each other minimally at the high plant populations and would be more tolerant of the high plant population. Canopy light interception of the unifoliate-leaf cultivars cannot be increased in the high plant densities used in this thesis, because higher population density would likely lead to increased mutual shading. Eastin (1969) suggested that there is an optimum leaf arrangement for each genotype-row spacing-population combination. Further research is needed to investigate the optimum row spacing because absence the maximum light interception possible (> 95%) showed that the row spacing was too wide. Studies of the relationship between canopy structure and crop productivity have been thoroughly reviewed by Trenbath and

Angus (1975). They concluded that leaf initiation could markedly affect the growth of C3 species. Furthermore, a mathematical model of canopy photosynthesis indicated that an erect canopy could have a 10-20% higher photosynthetic rate than a prostrate canopy, such as in many dicots (McCree and Keener, 1974). An erect leaf orientation gave an enhanced capacity to utilize greater available irradiation irrespective of position on the plant. However, some researchers found that that there were no advantages for crop growth in erect leaf structure for wheat (Stoskopf, 1967) and for barley (Angus et al., 1972); crops that have already formed erectile leaf and tiller structure. These contradictionary results have been discussed by Evans (1975), who suggested that the function of leaves at different levels of the crops may vary depending on the nature of the crops. Upright leaf orientation cultivars more efficiently converted intercepted solar energy into dry matter and seed (Duncan, 1971). However, unfoliate leaf cultivars had higher RUE than the fern-leaf cultivars in one out of four location-years. More research is needed to resolve this apparent contradiction.

Siddique et al. (1984) reported that leaf number was more important compared to leaf size in controlling LAI and hence the rate of canopy closure in the crop. Plant breeders should consider both traits (leaf number and size), when attempting to increase leaf area in chickpea.

Singh et al. (1982) proposed that breeding or selection for the ideotype to provide an open canopy for uniform distribution of radiation in the whole profile would enable the plant to bear pods in the lower horizons of the crop profile. Fern leaves have narrower leaflets and allow greater light penetration into the canopy

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compared to unifoliate leaves. This finding is supported by results in soybean and cassava plants (Fukai et al., 1984; Hicks et al., 1969). Loomis and Williams (1969) also suggested that the leaf arrangement in reduced-stature plants might be improved by reducing leaf width, or by arranging the leaves in a whorled pattern. Greater penetration of light into the lower part of the fern leaf canopy in this thesis may have contributed to an increase in both the photosynthetic ability of lower leaves and pod set at lower nodes. To increase light penetration, the canopy may be improved by using leaves with reduced leaf width (a diminutive or narrow leaflet trait), or arranging the leaves in a uniformly distributed pattern.

5.2 Optimum plant population for chickpea growth in Saskatchewan

Crop production researchers have conducted many studies to determine the optimum population density for chickpea. Unfortunately, there is no single recommendation for all environments, because optimum plant density varies depending on many unmanaged environmental factors, as well as on management factors such as soil fertility, cultivar selection, planting date, planting pattern, plant protection, and time of harvest (Modarres et al., 1998). Increased plant population densities can promote utilization of solar radiation by increasing maximum biomass and seasonal cumulative intercepted radiation. However, harvest index was decreased with high plant population density in two location-years.

In semi-arid Saskatchewan, rapid canopy development may be a disadvantage during dry years, because the increased early season exposure of leaves to full sunlight increases use of stored soil water if all other factors are equal. When more stored water is used early in the season, then less water is available

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during the critical pod filling period. In addition, if water does become limiting after flowering, high plant population densities will exacerbate a reduction in canopy photosynthesis and may result in less yield than moderate plant densities (Taylor, 1980; Reicosky et al., 1985). Although some researchers have found that increased density increased soybean and chickpea yield (Shibles and Weber, 1966; Egli, 1988; Jettner, et al., 1999; Regan et al., 2003), the densities studied were lower than the highest density in this experiment and many of the environments had a longer crop growing season of four to five months.

Manipulation of the radiation environment during different stages of crop development is a useful tool to evaluate the best leaf type for solar radiation capture in the short-growing season. The allocation of source (carbon metabolites) among chickpea plants will vary with source levels, population densities and leaf morphology, as well as environmental conditions. In general, the timing, intensity, and frequency of defoliation affected chickpea yield. Yield reduction was less sensitive to a single defoliation event during vegetative growth and first flower because indeterminate chickpea is able to develop new leaf area to compensate for any temporarily reduced assimilatory capacity. Little effect of defoliation was seen on biomass production, light interception, cumulative intercepted radiation, HI and yield. These findings were not surprising given the indeterminate growth habit and compensatory response of chickpea plants, as well as short-term fluctuations in the solar radiation condition that can occur in most location-years. Fehr et al. (1997) reported that determinate soybean cultivars were more affected by defoliation than indeterminate cultivars.

The chickpea plants in the thesis responded almost immediately to the shade treatment with reduced biomass, light interception and CGR, and plants recovered to the control levels when the shade treatment was removed. The shade treatment reduced cumulative intercepted radiation and yield with a resultant lower HI. Shading may cause reductions in photosynthesis and assimilate, and stimulate flower abortion. All the above make a significant contribution to total seasonal flower abortion (Hansen and Shibes, 1978; Huff and Dybing, 1980; Heitholt el al., 1980; Egli and Bruening, 2005). The reduction in HI and yield in this thesis showed that chickpea between late vegetative and early flowering growth, a period of two to three weeks, is sensitive to shading; HI and yield is closely coupled to the time when the first reproductive organs are formed. In soybean the early reproductive period (R1 to shortly past R5) translate to first flower to early seed fill, and this is most sensitive to altered source strength and CGR (Board and Harville, 1994). This period defines when the final pod numbers are formed (Board and Tan, 1995).

Under a light enrichment treatment, light is redistributed and lower leaves have more incident radiation in the crop (Begna et al., 1999). More light interception by lower leaves can be beneficial because the plant leaf is more efficient at lower irradiance (Loomis and Williams, 1969; Warren, 1981), because photosynthesis is not light saturated. Even though both flowering and pod development are the most sensitive growth stages affecting the final yield of chickpea (Prasad et al., 1978), the enrichment treatment initiated from early flowering through plant maturity affected yield more significantly than enrichment at the later pod formation stage. Thus, an increase in yield potential is possible by

improving the efficiency of light interception at flowering through cultural practices such as reduced row spacing, or by selecting cultivars with the best leaf type in light utilization, the fern leaf.

6.0 Conclusion and Future Research

6.1 Conclusion

Fern leaf cultivars produced significantly higher seed yields than cultivars with unifoliate leaves. The fern and unifoliate leaf type contributed to similar RUE for three out of four location-years. The fern leaf, however, exhibited higher maximum LI, greater seasonal cumulative intercepted radiation and a higher HI compared to the unifoliate leaf. Future high-yielding kabuli chickpea cultivars will likely come from increases in canopy LI and seasonal cumulative intercepted radiation and HI, but are unlikely to come from an increase in RUE. My study suggests that chickpea breeders could select cultivars with fern leaves for improved radiation interception, and these would be suited to the semi-arid short-season environments of Saskatchewan.

The impact of source-sink manipulation on chickpea yield depended on the stages of crop development when treatments were applied. Chickpea exhibited a varied response to defoliation, shade and light enrichment. This thesis highlighted the importance of the amount of light or irradiance around the early flowering stage. Defoliation at the vegetative growth and first flower stages had minor effects on chickpea yield. Plants responded significantly to the shade treatment by decreasing CGR, HI and yield compared to the control. Management and breeding practices should ensure that a crop makes efficient use of the solar radiation at flowering to

maximize chickpea yield. The light enrichment treatment demonstrated that total

incident radiation penetration further into the canopy resulted in increased

interception by lower leaves in the canopy, rather than just by upper canopy leaves,

and increased yield. Chickpea architecture that allows more leaf area to intercept

more of the incident radiation, with less radiation being transmitted to bare ground,

would improve chickpea yield. The fact that many canopies had less than 95% LI

for most location-years means that much improvement at the canopy and subsequent

yield level is needed, likely by reducing row space and striving for equidistant plant

spacing.

6.2 Future research

Future research can use plant modeling to design a chickpea canopy for

optimum LI by using a wider range of canopy types by varying the combination of

plant height, number of leaves, leaf and leaflet shape, leaf area index, as well as

population densities and planting configurations. The shape of maize was

accurately simulated using two-dimensional distribution of leaf area and leaf angles

(Steward et al., 2003). New hybrid cultivars of maize (1990's to present) respond

well to high population density and narrow rows (e.g., Pioneer hybrids widely

grown in the Mid West of USA)

In addition, research showed it is unlikely that an individual physiological or

morphological mechanism will directly affect yield determination (Turner et al.,

2001). A single gene difference for the leaf type being the sole factor responsible

for the performance of the six cultivars is unlikely. Further research is needed to

examine possible genetic linkages between leaf type as well as other phenotypical

traits and yield potential in chickpea. The cultivars used in this study are not isogenic. An alternative approach of this thesis could be to compare the fern leaf and unifoliate leaf populations derived from the crosses of such parents.

The results of manipulation of solar radiation environment depended on the choice of plant population density and row spacing, as well as development stages and selection of chickpea cultivars. In this thesis, two cultivars with different leaf morphology grown under high population density were chosen, combined with treatments applied at the vegetative, first flower and pod formation stages. In the future, the combination of another population density, row spacing and cultivar, as well as treatment stages could be studied to find the other critical periods in limiting chickpea yield potential. Moreover, the responses of yield components to defoliation, shading and light enrichment treatments need to be further investigated.

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Appendix 1

Table 1 Analysis of variance for the stand establishment of kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	61.7	1.4	0.2557	3	165.6	7.7	0.0005
Cultivar	5	105.4	2.4	0.0566	5	24.9	1.2	0.3478
Plant population	1	8256.4	189.4	<.0001	1	1036.7	48.4	<.0001
Cultivar × population	5	72.9	1.7	0.1689	5	46.0	2.2	0.0842
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	24.3	0.4	0.7327	3	201.4	3.5	0.0252
Cultivar	5	26.9	0.5	0.7909	5	323.6	5.7	0.0007
Plant population	1	4977.6	88.1	<.0001	1	4396.8	77.2	<.0001
Cultivar × population	5	30.5	0.5	0.7442	5	46.5	0.8	0.5463

Appendix 2

Table 1 Results from analysis of variance for biomass accumulation on individual dates at Saskatoon in 2003.

Source of variation	d.f.	Mean squares	*F value*	*P* value	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value
		36 DAS†			44 DAS			55 DAS		
Replication	3	196.3	1.6	0.2003	199.0	0.6	0.6517	471.0	0.7	0.5606
Cultivar	5	774.2	6.5	0.0003	764.4	2.1	0.0886	925.2	1.4	0.2610
Plant population	1	4521.7	37.7	<.0001	10666.0	29.5	<.0001	10715.9	15.9	0.0004
Cultivar × population	5	147.8	1.2	0.3171	411.9	1.1	0.3599	2346.4	3.5	0.0125
		62 DAS			71 DAS			79 DAS		
Replication	3	2682.6	1.2	0.3393	4307.0	1.6	0.2201	4307.0	1.6	0.2201
Cultivar	5	7326.1	3.2	0.0191	6327.6	2.3	0.0696	6327.6	2.3	0.0696
Plant population	1	6449.5	2.8	0.1042	22545.8	8.1	0.0075	22545.8	8.1	0.0075
Cultivar × population	5	1573.1	0.7	0.6411	1326.5	0.5	0.7905	1326.5	0.5	0.7905

†DAS is days after seeding

Appendix 3

Table 2 Results from analysis of variance for biomass accumulation on individual dates at Swift Current in 2004.

Source of variation	d.f.	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value
		47 DAS†			54 DAS			63 DAS		
Replication	3	52.5	0.7	0.5583	67.4	0.3	0.8515	1981.5	1.9	0.1491
Cultivar	5	629.4	8.4	<.0001	1113.8	4.3	0.0038	4168.1	4.0	0.0061
Plant population	1	4326.5	57.7	<.0001	3942.9	15.4	0.0004	25121.2	24.1	<.0001
Cultivar × population	5	232.1	3.1	0.0212	507.5	2.0	0.1077	414.5	0.4	0.8472
		73 DAS			83 DAS			94 DAS		
Replication	3	2611.2	0.7	0.5646	7020.3	1.1	0.3614	11264.7	0.7	0.5615
Cultivar	5	13027.9	3.4	0.0133	4941.9	0.8	0.573	43368.0	2.7	0.0388
Plant population	1	61131.6	16.2	0.0003	49248.3	7.8	0.0089	147.0	0.0	0.9247
Cultivar × population	5	2734.9	0.7	0.6110	4955.1	0.8	0.5716	18212.4	1.1	0.3669
		105 DAS			117 DAS					
Replication	3	2581.4	0.1	0.9412	17613.9	0.8	0.4874			
Cultivar	5	79993.0	4.1	0.0056	138366.2	6.5	0.0003			
Plant population	1	49.1	0.0	0.9605	11514.6	0.5	0.4668			
Cultivar × population	5	2788.1	0.1	0.9813	32542.7	1.5	0.2069			

† DAS is days after seeding

Appendix 4

Table 1 Results from analysis of variance for maximum above ground biomass of kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	3954.3	2.0	0.1327	3	13146.6	6.4	0.0015
Cultivar	5	7233.8	3.7	0.0095	5	734.6	0.4	0.8737
Plant population	1	16814.8	8.5	0.0063	1	16173.8	7.9	0.0084
Cultivar × population	5	1039.6	0.5	0.7544	5	3605.2	1.8	0.1498
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	11241.7	1.3	0.2870	3	1654.3	0.1	0.9399
Cultivar	5	4621.1	0.5	0.7450	5	67292.8	5.4	0.0010
Plant population	1	43296.1	5.1	0.0314	1	183.4	0.0	0.9042
Cultivar × population	5	6025.9	0.7	0.6250	5	6726.4	0.5	0.7450

Appendix 5

Table 1 Results from analysis of variance for crop growth rate of kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	8.0	2.5	0.0778	3	8.8	3.5	0.0266
Cultivar	5	19.7	6.2	0.0004	5	1.4	0.6	0.7407
Plant population	1	1.3	0.4	0.5214	1	0.0	0.0	0.9294
Cultivar × population	5	2.1	0.7	0.6572	5	2.4	1.0	0.4557
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	11.1	3.9	0.0165	3	2.8	0.5	0.6833
Cultivar	5	1.4	0.5	0.7763	5	25.1	4.6	0.0028
Plant population	1	7.4	2.6	0.1153	1	6.0	1.1	0.3052
Cultivar × population	5	1.1	0.4	0.8500	5	1.6	0.3	0.9185

Appendix 6

Table 1 Result from analysis of variance for maximum light interception of six kabuli chickpea cultivars at Swift Current in 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	93.8	3.1	0.0408	3	2.8	0.1	0.9595
Cultivar	5	164.5	5.4	0.0010	5	132.2	4.7	0.0028
Plant population	1	125.2	4.1	0.0507	1	22.7	0.8	0.3743
Cultivar × population	5	23.2	0.8	0.5845	5	10.4	0.4	0.8630
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	154.24	5.27	0.0044	3	15.5	0.9	0.4589
Cultivar	5	307.53	10.50	<.0001	5	511.0	29.3	<.0001
Plant population	1	23.23	0.79	0.3796	1	3.0	0.2	0.6823
Cultivar × population	5	23.73	0.81	0.5508	5	34.4	2.0	0.1089

Appendix 7

Table 1 Results from analysis of variance for light interception of six kabuli chickpea cultivars at Saskatoon in 2003.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		35 DAS†			44 DAS			57 DAS		
Replication	3	38.9	2.1	0.1196	90.1	3.7	0.0222	640.4	7.1	0.0008
Cultivar	5	23.5	1.3	0.3011	74.5	3.0	0.0236	105.6	1.2	0.3462
Population	1	1188.0	64.0	<.0001	697.2	28.3	<.0001	26.5	0.3	0.5918
Cultivar × population	5	26.7	1.4	0.2368	55.5	2.3	0.0725	30.8	0.3	0.8848
		62 DAS			79 DAS			89 DAS		
Replication	3	179.0	2.5	0.0758	218.0	10.5	<.0001	105.6	1.1	0.3559
Cultivar	5	235.8	3.3	0.0158	114.2	5.5	0.0009	39.9	0.4	0.8294
Population	1	299.3	4.2	0.0485	6.8	0.3	0.5696	76.1	0.8	0.3758
Cultivar × population	5	35.1	0.5	0.7798	45.2	2.2	0.0806	214.0	2.3	0.0712

†DAS is days after seeding

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Table 2. Results from analysis of variance for light interception of six kabuli chickpea cultivars at Saskatoon in 2004.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		42 DAS†			50 DAS			59 DAS		
Replication	3	182.9	4.3	0.0119	38.3	0.6	0.6047	151.4	3.4	0.0301
Cultivar	5	48.5	1.1	0.3638	173.2	2.8	0.0314	65.8	1.5	0.2284
Population	1	223.6	5.2	0.0289	2248.7	36.6	<.0001	1229.3	27.4	<.0001
Cultivar × population	5	43.3	1.0	0.4273	60.2	1.0	0.4438	48.2	1.1	0.3931
		69 DAS			78 DAS			86 DAS		
Replication	3	149.55	2.90	0.0497	30.86	0.50	0.6843	8.74	0.12	0.9493
Cultivar	5	247.24	4.79	0.0021	69.13	1.12	0.3679	225.60	3.03	0.0233
Population	1	9.21	0.18	0.6755	1.28	0.02	0.8864	3.85	0.05	0.8215
Cultivar × population	5	33.56	0.65	0.6633	108.00	1.75	0.1501	18.71	0.25	0.9362
		102 DAS								
Replication	3	675.15	10.12	<.0001						
Cultivar	5	423.77	6.35	0.0003						
Population	1	3.54	0.05	0.8193						
Cultivar × population	5	48.47	0.73	0.6083						

†DAS is days after seeding

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Table 3 Results from analysis of variance for light interception of six kabuli chickpea cultivars at Swift Current in 2003.

Source of variation	d.f.	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*
		28 DAS†			37 DAS			44 DAS		
Replication	3	74.0	11.9	<.0001	272.5	8.6	0.0002	626.7	13.0	<.0001
Cultivar	5	15.0	2.4	0.0564	24.4	0.8	0.5762	37.7	0.8	0.5704
Population	1	185.7	29.9	<.0001	565.3	17.9	0.0002	647.1	13.4	0.0009
Cultivar × population	5	9.4	1.5	0.2111	11.7	0.4	0.8648	49.5	1.0	0.4186
		51 DAS			58 DAS			65 DAS		
Replication	3	136.4	2.2	0.1112	29.1	0.7	0.5427	38.3	1.2	0.3199
Cultivar	5	145.0	2.3	0.0674	133.1	3.3	0.0153	114.8	3.6	0.0099
Population	1	559.0	8.9	0.0054	135.9	3.4	0.0743	30.6	1.0	0.3317
Cultivar × population	5	73.7	1.2	0.3455	24.0	0.6	0.7000	30.7	1.0	0.4479
		71 DAS			85 DAS					
Replication	3	64.9	1.7	0.1904	773.2	0.8	0.4800			
Cultivar	5	84.6	2.2	0.0792	499.1	0.5	0.7413			
Population	1	90.9	2.4	0.1348	437.2	0.5	0.4947			
Cultivar × population	5	28.6	0.7	0.5995	565.7	0.6	0.6876			

†DAS is days after seeding

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Table 4 Result from analysis of variance for light interception of six kabuli chickpea cultivars at Swift Current in 2004.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		53 DAS†			63 DAS			83 DAS		
Replication	3	56.2	2.2	0.1094	1020.5	9.6	0.0001	60.8	1.4	0.2738
Cultivar	5	216.1	8.4	<.0001	156.2	1.5	0.2279	253.8	5.7	0.0007
Population	1	1106.9	42.8	<.0001	176.1	1.7	0.2077	10.6	0.2	0.6310
Cultivar × population	5	8.4	0.3	0.8943	120.9	1.1	0.3622	34.9	0.8	0.5736
		97 DAS			105 DAS					
Replication	3	2.0	0.1	0.9797	518.0	6.3	0.0017			
Cultivar	5	644.1	19.4	<.0001	519.3	6.3	0.0003			
Population	1	5.6	0.2	0.6837	40.5	0.5	0.4884			
Cultivar × population	5	52.3	1.6	0.1950	87.0	1.1	0.4035			

†DAS is days after seeding

Appendix 8

Table 1 Result from analysis of variance for cumulative intercepted radiation of six kabuli chickpea cultivars at Saskatoon in 2003.

Source of variation	d.f.	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*
		6 DAS†			16 DAS			26 DAS		
Replication	3	853.6	2.8	0.0540	5505.3	2.8	0.0576	10586.1	2.8	0.0545
Cultivar	5	445.0	1.5	0.2260	2918.2	1.5	0.2281	5283.7	1.4	0.2485
Population	1	204.4	0.7	0.4171	1499.6	0.8	0.3920	3449.1	0.9	0.3454
Cultivar × population	5	190.2	0.6	0.6793	1295.8	0.7	0.6635	2412.6	0.6	0.6701
		36 DAS			46 DAS			56 DAS		
Replication	3	20285.8	3.1	0.0399	24122.9	3.0	0.0462	24487.8	2.6	0.0691
Cultivar	5	8301.8	1.3	0.3002	10394.1	1.3	0.2971	12691.7	1.3	0.2703
Population	1	13183.3	2.0	0.1650	22567.0	2.8	0.1053	32500.2	3.4	0.0725
Cultivar × population	5	4306.9	0.7	0.6571	5707.8	0.7	0.6263	7034.5	0.8	0.5953
		66 DAS			76 DAS			86 DAS		
Replication	3	22581.9	2.2	0.1061	20623.1	1.9	0.1496	20164.8	1.7	0.1798
Cultivar	5	15055.3	1.5	0.2262	17506.0	1.6	0.1851	19874.6	1.7	0.1608
Population	1	39393.8	3.9	0.0584	43871.8	4.0	0.0529	47628.5	4.1	0.0514
Cultivar × population	5	7863.9	0.8	0.5797	8445.5	0.8	0.5740	8993.3	0.8	0.5769

†DAS is days after seeding

Table 2 Result from analysis of variance for cumulative intercepted radiation of six kabuli chickpea cultivars at Saskatoon in 2004.

Source of variation	d.f.	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*	Mean Squares	*F value*	*P value*
		4 DAS†			14 DAS			24 DAS		
Replication	3	12.3	1	0.4051	58.4	1	0.4051	105.5	1	0.4051
Cultivar	5	12.3	1	0.4331	58.4	1	0.4331	105.5	1	0.4331
Population	1	12.3	1	0.3246	58.4	1	0.3246	105.5	1	0.3246
Cultivar × population	5	12.3	1	0.4331	58.4	1	0.4331	105.5	1	0.4331
		34 DAS			44 DAS			54 DAS		
Replication	3	197.5	1.2	0.3391	454.4	1.8	0.1594	457.7	1.5	0.2347
Cultivar	5	146.2	0.9	0.5180	97.3	0.4	0.8498	224.4	0.7	0.6048
Population	1	178.4	1.1	0.3131	3.3	0.0	0.9090	1861.0	6.1	0.0191
Cultivar × population	5	169.3	1.0	0.4353	350.4	1.4	0.2437	505.4	1.7	0.1749
		64 DAS			74 DAS			84 DAS		
Replication	3	413.2	1.2	0.3446	402.3	0.9	0.4444	408.1	0.8	0.5267
Cultivar	5	517.7	1.4	0.2370	1047.2	2.4	0.0597	1767.0	3.3	0.0165
Population	1	5307.4	14.7	0.0005	8072.2	18.4	0.0001	8256.9	15.3	0.0004
Cultivar × population	5	574.2	1.6	0.1891	610.3	1.4	0.2542	642.6	1.2	0.3349
		94 DAS								
Replication	3	478.7	0.7	0.5500						
Cultivar	5	2730.7	4.1	0.0054						
Population	1	7510.1	11.2	0.0020						
Cultivar × population	5	670.1	1.0	0.4325						

†DAS is days after seeding

Table 3 Result from analysis of variance for cumulative intercepted radiation of six kabuli chickpea cultivars at Swift Current in 2003.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		30 DAS†			40 DAS			50 DAS		
Replication	3	31.3	5.8	0.0026	392.1	14.7	<.0001	1131.5	12.6	<.0001
Cultivar	5	7.0	1.3	0.2910	31.8	1.2	0.3338	154.1	1.7	0.1573
Plant population	1	86.3	16.0	0.0003	859.3	32.2	<.0001	2540.5	28.4	<.0001
Cultivar × population	5	5.4	1.0	0.4278	25.4	1.0	0.4607	91.8	1.0	0.4185
		60 DAS			70 DAS			80 DAS		
Replication	3	1879.5	9.3	0.0001	1959.9	6.2	0.0018	1536.2	3.2	0.0373
Cultivar	5	482.1	2.4	0.0589	798.5	2.5	0.0484	796.1	1.6	0.1770
Plant population	1	5153.2	25.6	<.0001	8040.8	25.4	<.0001	9861.4	20.3	<.0001
Cultivar × population	5	239.6	1.2	0.3362	411.0	1.3	0.2878	553.4	1.1	0.3591

†DAS is days after seeding

Table 4 Result from analysis of variance for cumulative intercepted radiation of six kabuli chickpea cultivars at Swift Current in 2004.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		5 DAS†			15 DAS			25 DAS		
Replication	3	2.8	0.1	0.9592	11.8	0.1	0.9546	38.9	0.1	0.9463
Cultivar	5	40.4	1.5	0.2300	168.9	1.6	0.2029	522.4	1.6	0.1758
Plant population	1	102.1	3.7	0.0634	466.6	4.3	0.0468	1621.2	5.1	0.0306
Cultivar × population	5	60.3	2.2	0.0806	252.5	2.3	0.0664	782.3	2.5	0.0530
		35 DAS			45 DAS			55 DAS		
Replication	3	62.0	0.1	0.9543	283.0	0.3	0.8439	857.4	0.7	0.5582
Cultivar	5	1040.7	1.8	0.1348	2734.6	2.7	0.0406	4482.3	3.7	0.0095
Plant population	1	3615.5	6.3	0.0168	11190.2	10.8	0.0024	19326.0	15.8	0.0004
Cultivar × population	5	1494.0	2.6	0.0420	2969.7	2.9	0.0292	3750.8	3.1	0.0221
		65 DAS			75 DAS			85 DAS		
Replication	3	1750.6	1.5	0.2426	2493.2	2.3	0.1007	3145.2	2.9	0.0491
Cultivar	5	6089.4	5.1	0.0014	7080.9	6.4	0.0003	8128.0	7.5	<.0001
Plant population	1	26820.3	22.4	<.0001	29892.8	27.0	<.0001	30648.4	28.3	<.0001
Cultivar × population	5	4288.2	3.6	0.0107	4423.1	4.0	0.0061	4409.8	4.1	0.0054
		95 DAS			105 DAS			115 DAS		
Replication	3	4035.1	3.6	0.0242	5175.5	4.2	0.0127	7256.2	5.0	0.0058
Cultivar	5	10090.3	8.9	<.0001	12897.3	10.5	<.0001	17740.0	12.2	<.0001
Plant population	1	30900.2	27.4	<.0001	31849.0	25.8	<.0001	33987.1	23.4	<.0001
Cultivar × population	5	4426.1	3.9	0.0067	4587.2	3.7	0.0088	4862.1	3.4	0.0149

Appendix 9

Table 1 Result from analysis of variance for seasonal cumulative intercepted radiation of six kabuli chickpea cultivars at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	20641.6	1.7	0.1839	3	1296.9	2.2	0.1032
Cultivar	5	20885.0	1.7	0.1551	5	618.3	1.1	0.3985
Plant population	1	49272.4	4.1	0.0515	1	9864.5	17.0	0.0002
Cultivar × population	5	9251.4	0.8	0.5806	5	577.1	1.0	0.4376
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	478.7	0.7	0.5500	3	7642.9	5.1	0.0053
Cultivar	5	2730.7	4.1	0.0054	5	18605.9	12.4	<.0001
Plant population	1	7510.1	11.2	0.0020	1	34390.8	22.9	<.0001
Cultivar × population	5	670.1	1.0	0.4325	5	4905.0	3.3	0.0168

Appendix 10

Table 1 Result from analysis of variance for harvest index of kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	0.01	1.34	0.2787	3	0.00	0.76	0.5248
Cultivar	5	0.04	6.67	0.0002	5	0.05	44.10	<.0001
Plant population	1	0.02	3.04	0.0906	1	0.01	7.17	0.0116
Cultivar × population	5	0.01	1.40	0.2487	5	0.00	0.60	0.6980
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	0.00	0.89	0.4561	3	0.00	0.39	0.7632
Cultivar	5	0.04	7.58	<.0001	5	0.10	23.16	<.0001
Plant population	1	0.00	0.06	0.8022	1	0.01	2.11	0.1559
Cultivar × population	5	0.00	0.78	0.5712	5	0.00	0.71	0.6235

Appendix 11

Table 1 Result from analysis of variance for yield of kabuli chickpea at Saskatoon and Swift Current in 2003 and 2004.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	447469.4	20.3	<.0001	3	128509.5	19.8	<.0001
Cultivar	5	192695.4	8.8	<.0001	5	201597.6	31.0	<.0001
Plant population	1	34771.0	1.6	0.2175	1	11331.4	1.7	0.1956
Cultivar × population	5	19735.5	0.9	0.4945	5	6167.2	1.0	0.4624
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	233316.1	16.6	<.0001	3	82087.4	2.2	0.1042
Cultivar	5	577438.0	41.0	<.0001	5	10196092.6	275.8	<.0001
Plant population	1	31626.5	2.2	0.1437	1	2103800.0	56.9	<.0001
Cultivar × population	5	37711.2	2.7	0.0389	5	135020.9	3.7	0.0097

Appendix 12

Table 1 Result from analysis of variance for stand establishment of kabuli chickpea at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	36.6	0.5	0.7025	3	56.6	0.6	0.6370
Canopy treatment	3	61.9	0.8	0.5051	3	53.3	0.5	0.6587
Cultivar	1	488.3	6.4	0.0199	1	66.1	0.7	0.4211
Treatment × cultivar	3	11.4	0.2	0.9300	3	70.7	0.7	0.5512
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	26.1	0.5	0.6954	3	251.0	2.4	0.0897
Canopy treatment	5	10.6	0.2	0.9617	5	34.5	0.3	0.8952
Cultivar	1	633.5	11.7	0.0017	1	157.0	1.5	0.2333
Treatment × cultivar	5	98.6	1.8	0.1349	5	75.4	0.7	0.6214
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	2	294.8	3.5	0.0497	3	81.8	1.4	0.2613
Canopy treatment	5	28.2	0.3	0.8878	5	59.4	1.0	0.4253
Cultivar	1	355.3	4.2	0.0535	1	165.0	2.8	0.1027
Treatment × cultivar	5	68.1	0.8	0.5609	5	82.8	1.4	0.2451

Appendix 13

Table 1 Result from analysis of variance for plant height at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	44.2	3.0	0.0513	3	47.2	5.8	0.0047
Cultivar	1	4.9	0.3	0.5680	1	171.1	21.1	0.0002
Canopy treatment	3	124.7	8.6	0.0006	3	245.8	30.3	<.0001
Cultivar × treatment	3	0.1	0.0	0.9988	3	13.8	1.7	0.1976
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	9.1	0.8	0.5146	3	407.8	11.6	<.0001
Cultivar	1	2.3	0.2	0.6605	1	68.6	2.0	0.1715
Canopy treatment	3	28.8	2.5	0.0531	3	160.9	4.6	0.0028
Cultivar × treatment	3	6.6	0.6	0.7253	3	20.3	0.6	0.7169
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	21.9	1.5	0.2487	3	25.2	2.9	0.0489
Cultivar	1	26.5	1.8	0.1937	1	48.0	5.5	0.0247
Canopy treatment	3	7.1	0.5	0.7863	3	22.6	2.6	0.0429
Cultivar × treatment	3	14.0	1.0	0.4670	3	9.1	1.0	0.4082

Table 2 Result from analysis of variance for low pod height at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	3.5	0.4	0.7583	3	15.4	3.4	0.036
Cultivar	1	11.9	1.4	0.2579	1	120.1	26.7	<.0001
Canopy treatment	3	79.5	9.1	0.0005	3	153.4	34.1	<.0001
Cultivar × treatment	3	8.0	8.0	0.4524	3	19.0	4.2	0.0172
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	20.0	2.5	0.0811	3	19.4	1.7	0.1892
Cultivar	1	93.5	11.5	0.0019	1	230.6	20.0	<.0001
Canopy treatment	3	14.0	1.7	0.1574	3	21.8	1.9	0.1218
Cultivar × treatment	3	7.7	0.9	0.4673	3	2.3	0.2	0.9596
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	496.4	11.4	0.0004	3	2.6	0.3	0.8518
Cultivar	1	167.6	3.9	0.0630	1	90.8	9.1	0.0048
Canopy treatment	3	143.4	3.3	0.0236	3	23.2	2.3	0.0641
Cultivar × treatment	3	47.4	1.1	0.3950	3	6.5	0.7	0.6645

Appendix 14

Table 1 Result from analysis of variance for biomass accumulation at individual dates at Saskatoon in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		37 DAS†			42 DAS			55 DAS		
Replication	3	671.2	4	0.0213	1538.8	4.6	0.0123	3118.9	4.3	0.0167
Canopy treatment	3	627.1	3.7	0.027	454.6	1.4	0.2797	3261.7	4.5	0.0141
Cultivar	1	25.2	0.2	0.7022	1.3	0	0.9501	126.3	0.2	0.6815
Treatment × cultivar	3	105.3	0.6	0.6055	644.7	1.9	0.154	232.3	0.3	0.8119
		62 DAS			72 DAS			89 DAS		
Replication	3	5644.2	3.7	0.0289	14472.6	5.7	0.0052	27427	4.8	0.0109
Canopy treatment	3	19170.5	12.4	<.0001	24429.1	9.6	0.0003	33827	5.9	0.0044
Cultivar	1	4.2	0	0.959	3.8	0	0.9698	8414.2	1.5	0.2398
Treatment × cultivar	3	2754.8	1.8	0.1807	10078.9	4	0.0222	121.7	0	0.9957

†DAS is days after seeding

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Table 2 Result from analysis of variance for biomass accumulation at individual dates at Swift Current in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		30 DAS†			37 DAS			44 DAS		
Replication	3	69.5	0.4	0.7555	393.3	1.9	0.1653	948.3	3.2	0.0462
Canopy treatment	3	117.9	0.7	0.5765	169.0	0.8	0.5054	762.3	2.5	0.0842
Cultivar	1	237.7	1.4	0.2566	1016.0	4.8	0.0392	9311.6	31.0	<.0001
Treatment × cultivar	3	126.0	0.7	0.5501	719.3	3.4	0.0359	99.4	0.3	0.8031
		50 DAS			57 DAS			65 DAS		
Replication	3	1896.4	4.3	0.0159	3824.3	1.0	0.4317	5967.9	0.8	0.4915
Canopy treatment	3	2176.5	5.0	0.0093	5157.9	1.3	0.304	7479.3	1.0	0.3945
Cultivar	1	9839.3	22.5	0.0001	4621.1	1.2	0.2946	2992.5	0.4	0.5255
Treatment × cultivar	3	803.7	1.8	0.1720	3763.2	0.9	0.4386	2785.7	0.4	0.7628
		71 DAS								
Replication	3	5489.3	0.6	0.6186						
Canopy treatment	3	7716.4	0.9	0.4817						
Cultivar	1	14592.5	1.6	0.2188						
Treatment × cultivar	3	7919.9	0.9	0.4706						

†DAS is days after seeding

Table 3 Result from analysis of variance for biomass accumulation at individual dates at Saskatoon in 2004.

Source of variation	d.f.	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value
		36 DAS†			41 DAS			57 DAS		
Replication	3	48.1	0.7	0.5826	268.5	0.7	0.5628	1768.7	0.7	0.5804
Canopy treatment	5	195.0	2.7	0.0389	1092.0	2.8	0.0316	6937.1	2.6	0.0432
Cultivar	1	225.2	3.1	0.0881	67.9	0.2	0.6783	7973.1	3.0	0.0931
Treatment × cultivar	5	21.6	0.3	0.9111	387.8	1.0	0.4325	2305.4	0.9	0.5149
		68 DAS			77 DAS			92 DAS		
Replication	3	6304.3	0.9	0.4374	32492.6	3.6	0.0228	26784.9	2.4	0.0869
Canopy treatment	5	48448.3	7.2	0.0001	60577.1	6.8	0.0002	150389.7	13.4	<.0001
Cultivar	1	6901.2	1.0	0.3205	48305.8	5.4	0.0264	44735.1	4.0	0.0542
Treatment × cultivar	5	695.5	0.1	0.9909	3116.5	0.4	0.8795	10086.4	0.9	0.4938
		106 DAS								
Replication	3	30104.5	1.3	0.2948						
Canopy treatment	5	208393.7	8.9	<.0001						
Cultivar	1	13163.4	0.6	0.4583						
Treatment × cultivar	5	16814.5	0.7	0.6135						

†DAS is days after seeding

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Table 4 Result from analysis of variance for biomass accumulation at individual dates at Swift Current in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		44 DAS†			51 DAS			71 DAS		
Replication	3	164.9	0.8	0.4914	353.4	0.8	0.532	48260.9	5.9	0.0025
Canopy treatment	5	161.5	0.8	0.5544	265.9	0.6	0.7283	29320.2	3.6	0.011
Cultivar	1	480.7	2.4	0.1312	2127.4	4.5	0.0416	48279.7	5.9	0.0211
Treatment × cultivar	5	239.3	1.2	0.3342	651.7	1.4	0.2581	7645.4	0.9	0.4751
		80 DAS			91 DAS			102 DAS		
Replication	3	32383.3	3.6	0.0225	60281.0	5.1	0.0052	75122.0	4.8	0.0073
Canopy treatment	5	66224.7	7.5	<.0001	35325.9	3.0	0.0247	25246.7	1.6	0.1878
Cultivar	1	935.8	0.1	0.7476	3622.6	0.3	0.5836	935.8	0.1	0.8092
Treatment × cultivar	5	19667.6	2.2	0.0764	34282.2	2.9	0.0281	8843.4	0.6	0.7297
		115 DAS								
Replication	3	22734.0	0.8	0.4887						
Canopy treatment	5	61068.3	2.2	0.0756						
Cultivar	1	251.7	0.0	0.9244						
Treatment × cultivar	5	4512.0	0.2	0.974						

†DAS is days after seeding

Table 5 Result from analysis of variance for biomass accumulation at individual dates at Saskatoon in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		53 DAS†			62 DAS			70 DAS		
Replication	2	457.1	1.2	0.3278	2088.5	1.4	0.2644	861.6	0.3	0.7520
Canopy treatment	5	389.1	1.0	0.4411	3170.7	2.2	0.0986	9513.6	3.2	0.0269
Cultivar	1	11577.1	29.8	<.0001	107242.8	72.8	<.0001	257705.5	86.4	<.0001
Treatment × cultivar	5	150.4	0.4	0.8519	1021.0	0.7	0.6342	4894.6	1.6	0.1928
		78 DAS			88 DAS			102 DAS		
Replication	2	221.8	0.1	0.9520	3986.5	0.3	0.7784	3876.8	0.1	0.8673
Canopy treatment	5	7995.4	1.8	0.1616	22118.6	1.4	0.2624	18133.3	0.7	0.6503
Cultivar	1	345382.5	76.7	<.0001	512072.0	32.6	<.0001	491642.2	18.2	0.0003
Treatment × cultivar	5	14172.1	3.2	0.0283	6750.6	0.4	0.823	25670.0	1.0	0.4705
		112 DAS			119 DAS					
Replication	2	14744.5	1.1	0.3648	10200.5	1.3	0.3020			
Canopy treatment	5	18159.2	1.3	0.3002	22018.2	2.7	0.0468			
Cultivar	1	719426.1	51.6	<.0001	1275359.0	158.6	<.0001			
Treatment × cultivar	5	18509.8	1.3	0.2905	2631.9	0.3	0.8909			

†DAS is days after seeding

Table 6 Result from analysis of variance for biomass accumulation at individual dates at Swift Current in 2005.

Source of variation	d.f.	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value
		48 DAS†			55 DAS			63 DAS		
Replication	3	468.4	0.7	0.5598	1407.2	1.1	0.3621	1825.0	0.6	0.6416
Canopy treatment	5	1417.6	2.1	0.0885	2626.6	2.1	0.0961	15480.6	4.8	0.0021
Cultivar	1	37714.5	56.2	<.0001	51709.8	40.5	<.0001	309602.6	96.0	<.0001
Treatment × cultivar	5	743.0	1.1	0.3752	1533.6	1.2	0.3302	2680.0	0.8	0.5373
		71 DAS			79 DAS			90 DAS		
Replication	3	18709.0	2.5	0.0742	1192.5	0.1	0.9377	12097.6	1.0	0.4182
Canopy treatment	5	21186.3	2.9	0.0296	20365.0	2.3	0.0647	25397.9	2.0	0.0988
Cultivar	1	254873.5	34.5	<.0001	312454.8	35.7	<.0001	208734.6	16.8	0.0003
Treatment × cultivar	5	15648.3	2.1	0.0882	8065.6	0.9	0.4794	12258.6	1.0	0.4423
		97 DAS			104 DAS			125 DAS		
Replication	3	3260.0	0.4	0.7768	31097.8	2.1	0.1217	26796.2	2.0	0.1267
Canopy treatment	5	17094.9	1.9	0.1162	8851.7	0.6	0.7059	6704.2	0.5	0.7655
Cultivar	1	72656.4	8.2	0.0072	1931.2	0.1	0.7215	21508.6	1.6	0.2091
Treatment × cultivar	5	5505.6	0.6	0.6848	5401.9	0.4	0.8711	16158.6	1.2	0.3161

†DAS is days after seeding

Appendix 15

Table 1 Result from analysis of variance for maximum biomass at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation		2003 Saskatoon				2003 Swift Current		
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	27794.8	5.2	0.0078	3	323.7	0.6	0.6547
Canopy treatment	3	32014.0	6.0	0.0042	3	496.3	0.8	0.4867
Cultivar	1	6921.8	1.3	0.2692	1	587.1	1.0	0.3299
Treatment × cultivar	3	484.9	0.1	0.9646	3	129.3	0.2	0.8821
Source of variation		2004 Saskatoon				2004 Swift Current		
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	35703.7	2.7	0.0641	3	57514.9	3.5	0.0255
Canopy treatment	5	178265.4	13.3	<.0001	5	42554.2	2.6	0.0430
Cultivar	1	282.0	0.0	0.8856	1	8562.1	0.5	0.4741
Treatment × cultivar	5	7112.7	0.5	0.7517	5	3112.5	0.2	0.9640
Source of variation		2005 Saskatoon				2005 Swift Current		
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	2	803.9	1.2	0.3303	3	9871.6	1.8	0.1616
Canopy treatment	5	746.6	1.1	0.3973	5	9719.5	1.8	0.1405
Cultivar	1	100104.5	145.5	<.0001	1	23610.5	4.4	0.0444
Treatment × cultivar	5	559.9	0.8	0.5532	5	9432.9	1.8	0.1518

Appendix 16

Table 1 Result from analysis of variance for crop growth rate at individual dates at Saskatoon in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		42 DAS†			55 DAS		
Replication	3	18.2	1.6	0.2163	12.5	4.0	0.0214
Canopy treatment	3	6.1	0.5	0.6593	36.1	11.6	0.0001
Cultivar	1	1.5	0.1	0.7169	0.6	0.2	0.667
Treatment × cultivar	3	28.8	2.6	0.0832	6.5	2.1	0.1345
		62 DAS			72 DAS		
Replication	3	12.9	0.4	0.7377	34.3	1.9	0.1574
Canopy treatment	3	177.6	5.8	0.0047	16.4	0.9	0.4503
Cultivar	1	3.6	0.1	0.7347	0.0	0	0.9978
Treatment × cultivar	3	65.9	2.2	0.1231	50.3	2.8	0.0642

†DAS is days after seeding

Table 2 Result from analysis of variance for crop growth rate at individual dates at Swift Current in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		37 DAS†			44 DAS		
Replication	3	2.5	0.3	0.8046	4.9	0.6	0.6051
Canopy treatment	3	0.7	0.1	0.9661	7.2	0.9	0.4477
Cultivar	1	5.0	0.7	0.4281	85.1	10.9	0.0035
Treatment × cultivar	3	12.3	1.6	0.2174	13.0	1.7	0.2062
		55 DAS			62 DAS		
Replication	3	44.5	2.6	0.0776	23.9	0.2	0.8903
Canopy treatment	3	17.9	1.1	0.3892	36.3	0.3	0.8144
Cultivar	1	0.2	0.0	0.9169	19.8	0.2	0.6826
Treatment × cultivar	3	29.2	1.7	0.193	47.7	0.4	0.7447

†DAS is days after seeding

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Table 3 Result from analysis of variance for crop growth rate at individual dates at Saskatoon in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		41 DAS†			57 DAS		
Replication	3	16.1	0.7	0.5416	8.6	0.8	0.5277
Canopy treatment	3	20.4	0.9	0.4757	28.3	2.5	0.0503
Cultivar	1	21.6	1.0	0.3292	37.1	3.3	0.0796
Treatment × cultivar	3	15.3	0.7	0.6298	8.1	0.7	0.6194
		68 DAS			77 DAS		
Replication	3	35.7	0.5	0.7167	191.4	1.1	0.3782
Canopy treatment	3	266.2	3.4	0.0145	275.3	1.5	0.2083
Cultivar	1	0.2	0.0	0.9556	231.8	1.3	0.2648
Treatment × cultivar	3	44.5	0.6	0.7259	31.6	0.2	0.9697

†DAS is days after seeding

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Table 4 Result from analysis of variance for crop growth rate at individual dates at Swift Current in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		51 DAS†			71 DAS		
Replication	3	6.2	0.6	0.6493	102.3	4.4	0.0108
Canopy treatment	3	6.4	0.6	0.724	74.1	3.2	0.0194
Cultivar	1	11.9	1.1	0.3114	75.7	3.2	0.0817
Treatment × cultivar	3	4.1	0.4	0.8706	25.8	1.1	0.3803
		80 DAS			91 DAS		
Replication	3	378.5	2.7	0.0687	92.6	0.6	0.635
Canopy treatment	3	194.1	1.4	0.2687	421.8	2.6	0.042
Cultivar	1	33.9	0.2	0.6291	49.1	0.3	0.5846
Treatment × cultivar	3	218.7	1.5	0.212	354.1	2.2	0.0778

†DAS is days after seeding

Table 5 Result from analysis of variance for crop growth rate at individual dates at Saskatoon in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		62 DAS†			70 DAS		
Replication	3	8.2	0.6	0.5357	4.2	0.1	0.917
Canopy treatment	3	26.9	2.1	0.1052	52.0	1.1	0.404
Cultivar	1	578.4	45.2	<.0001	464.8	9.6	0.0055
Treatment × cultivar	3	13.1	1.0	0.4285	30.0	0.6	0.6874
		78 DAS			88 DAS		
Replication	3	16.4	0.3	0.7696	42.4	0.3	0.7659
Canopy treatment	3	13.8	0.2	0.9487	139.9	0.9	0.5045
Cultivar	1	108.7	1.8	0.1994	112.1	0.7	0.4074
Treatment × cultivar	3	103.3	1.7	0.1863	22.8	0.2	0.9792

†DAS is days after seeding

Table 6 Result from analysis of variance for crop growth rate at individual dates at Swift Current in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		55 DAS†			63 DAS		
Replication	3	69.8	1.5	0.2463	45.5	0.5	0.666
Canopy treatment	3	41.7	0.9	0.5146	248.8	2.9	0.0286
Cultivar	1	22.3	0.5	0.5008	1692.3	19.7	<.0001
Treatment × cultivar	3	28.1	0.6	0.7133	17.6	0.2	0.9583
		71 DAS			79 DAS		
Replication	3	240.5	2.2	0.1043	255.6	1.3	0.2788
Canopy treatment	3	294.4	2.7	0.0366	176.8	0.9	0.4768
Cultivar	1	41.4	0.4	0.5407	45.7	0.2	0.6279
Treatment × cultivar	3	186.6	1.7	0.1571	320.9	1.7	0.1669

†DAS is days after seeding

Appendix 17

Table 1 Result from analysis of variance for light interception at individual dates at Saskatoon in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		35 DAS†			44 DAS			57 DAS		
Replication	3	96.8	2.6	0.0834	374.5	13.6	<.0001	581.8	11.6	0.0001
Canopy treatment	3	54.1	1.4	0.2641	134.2	4.9	0.0101	774.6	15.4	<.0001
Cultivar	1	11.4	0.3	0.5901	53.3	1.9	0.1791	5.3	0.1	0.7485
Treatment × cultivar	3	42.3	1.1	0.3669	21.1	0.8	0.5271	11.5	0.2	0.8756
		62 DAS			79 DAS			89 DAS		
Replication	3	30.3	0.5	0.6921	273.7	8.4	0.0008	101.9	1.3	0.3144
Canopy treatment	3	19.3	0.3	0.8154	210.7	6.4	0.0029	207.0	2.6	0.0828
Cultivar	1	11.4	0.2	0.6716	54.9	1.7	0.2096	116.9	1.4	0.2431
Treatment × cultivar	3	86.7	1.4	0.2690	14.9	0.5	0.7180	48.0	0.6	0.6267

†DAS is days after seeding

Table 2 Result from analysis of variance for light interception at individual dates at Swift Current in 2003.

Source of variation	d.f.	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value	Mean squares	*F* value	*P* value
		28 DAS†			37 DAS			44 DAS		
Replication	3	55.1	4.0	0.0223	19.6	0.7	0.5731	44.3	0.1	0.9711
Canopy treatment	3	59.8	4.3	0.0165	56.0	1.9	0.1536	844.3	1.5	0.2466
Cultivar	1	212.4	15.2	0.0008	416.5	14.5	0.0010	525.0	0.9	0.3470
Treatment × cultivar	3	31.3	2.2	0.1132	15.5	0.5	0.6618	414.0	0.7	0.5456
		51 DAS			58 DAS			65 DAS		
Replication	3	3.7	0.1	0.9362	63.0	0.6	0.6295	84.8	2.2	0.1159
Canopy treatment	3	579.9	21.5	<.0001	377.6	3.5	0.0327	211.5	5.5	0.0058
Cultivar	1	38.4	1.4	0.2455	62.8	0.6	0.4525	21.6	0.6	0.4609
Treatment × cultivar	3	453.4	16.8	<.0001	48.6	0.5	0.7171	16.6	0.4	0.7311
		71 DAS			85 DAS					
Replication	3	168.0	1.9	0.1653	22.7	0.6	0.6232			
Canopy treatment	3	197.2	2.2	0.1183	73.3	1.9	0.1549			
Cultivar	1	25.3	0.3	0.6010	7.6	0.2	0.6595			
Treatment × cultivar	3	62.3	0.7	0.5658	21.3	0.6	0.6460			

†DAS is days after seeding

Table 3 Result from analysis of variance for light interception at individual dates at Saskatoon in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		41 DAS†			49 DAS			58 DAS		
Replication	3	28.6	0.6	0.6369	49.4	1.3	0.3069	33.3	2.0	0.1528
Canopy treatment	3	310.3	6.3	0.0033	809.1	21.0	<.0001	902.2	52.8	<.0001
Cultivar	1	82.3	1.7	0.2115	771.5	20.0	0.0002	1699.5	99.4	<.0001
Treatment × cultivar	3	19.3	0.4	0.7624	159.3	4.1	0.019	65.9	3.9	0.0241
		68 DAS			77 DAS			85 DAS		
Replication	3	34.1	0.4	0.7860	84.2	0.7	0.5536	6.8	0.1	0.9646
Canopy treatment	3	162.2	1.7	0.1995	111.1	0.9	0.4369	65.7	0.9	0.4700
Cultivar	1	1.3	0.0	0.9072	6.3	0.1	0.8186	595.2	7.9	0.0104
Treatment × cultivar	3	138.1	1.4	0.2595	50.5	0.4	0.7342	53.7	0.7	0.5537
		101 DAS								
Replication	3	151.4	1.3	0.3085						
Canopy treatment	3	8.9	0.1	0.9727						
Cultivar	1	251.5	2.1	0.1603						
Treatment × cultivar	3	80.1	0.7	0.5769						

†DAS is days after seeding

Table 4 Result from analysis of variance for light interception at individual dates at Swift Current in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value
		50 DAS†			60 DAS		
Replication	3	991.8	28.0	<.0001	2052.8	29.7	<.0001
Canopy treatment	3	168.9	4.8	0.011	77.6	1.1	0.3629
Cultivar	1	19.5	0.6	0.4665	85.8	1.2	0.2779
Treatment × cultivar	3	40.0	1.1	0.3604	64.9	0.9	0.4398
		80 DAS			102 DAS		
Replication	3	74.9	3.0	0.0412	19.3	1.3	0.3057
Canopy treatment	3	19.8	0.8	0.5057	5.8	0.4	0.7619
Cultivar	1	86.0	3.5	0.0763	68.5	4.6	0.0447
Treatment × cultivar	3	9.5	0.4	0.7644	6.7	0.5	0.7219

†DAS is days after seeding

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Table 5 Result from analysis of variance for light interception at individual dates at Saskatoon in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		54 DAS†			62 DAS			71 DAS		
Replication	2	107.6	1.3	0.3051	74.4	0.4	0.6874	30.8	0.7	0.5294
Canopy treatment	3	51.9	0.6	0.6097	624.9	3.2	0.0571	372.7	8.1	0.0027
Cultivar	1	2980.8	36.1	<.0001	9655.0	50.1	<.0001	6388.3	138.5	<.0001
Treatment × cultivar	3	26.9	0.3	0.8067	167.0	0.9	0.4834	102.7	2.2	0.1336
		79 DAS			89 DAS			100 DAS		
Replication	2	12.3	0.2	0.7996	134.1	1.5	0.2670	86.5	1.0	0.3979
Canopy treatment	3	229.0	4.2	0.0295	272.5	3.0	0.0707	206.1	2.4	0.1189
Cultivar	1	3703.3	68.4	<.0001	1995.9	21.8	0.0004	529.9	6.1	0.0285
Treatment × cultivar	3	62.1	1.2	0.3698	30.9	0.3	0.7985	62.2	0.7	0.5617
		108 DAS			130 DAS					
Replication	2	29.1	0.2	0.8252	43.8	0.4	0.6859			
Canopy treatment	3	231.4	1.6	0.2488	173.9	1.5	0.2512			
Cultivar	1	730.7	4.9	0.0454	3225.3	28.6	0.0001			
Treatment × cultivar	3	136.4	0.9	0.4614	33.9	0.3	0.8246			

†DAS is days after seeding

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Table 6 Result from analysis of variance for light interception at individual dates at Swift Current in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		55 DAS†			63 DAS			71 DAS		
Replication	3	107.3	1.7	0.2087	142.0	0.8	0.5058	66.4	1.4	0.2864
Canopy treatment	3	379.6	5.8	0.0046	520.1	2.9	0.0566	362.9	7.4	0.0015
Cultivar	1	1625.0	25.0	<.0001	2648.4	15.0	0.0009	2371.5	48.1	<.0001
Treatment × cultivar	3	253.4	3.9	0.0234	170.5	1.0	0.4276	136.2	2.8	0.0674
		79 DAS			97 DAS			104 DAS		
Replication	3	46.7	1.2	0.3492	28.1	1.0	0.407	109.9	2.9	0.0582
Canopy treatment	3	118.1	2.9	0.0574	85.3	3.1	0.0498	192.8	5.1	0.0082
Cultivar	1	1614.5	40.1	<.0001	0.2	0.0	0.9288	172.3	4.6	0.0445
Treatment × cultivar	3	35.0	0.9	0.4733	98.9	3.6	0.0314	33.3	0.9	0.4667

†DAS is days after seeding

Appendix 18

Table 1 Result from analysis of variance for maximum light interception of kabuli chickpea at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	139.0	3.8	0.0245	3	78.2	1.3	0.3036
Canopy treatment	3	72.3	2.0	0.1455	3	503.7	8.3	0.0008
Cultivar	1	0.2	0.0	0.9379	1	47.8	0.8	0.3843
Treatment × cultivar	3	91.0	2.5	0.0862	3	118.9	2.0	0.1505
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	62.0	2.3	0.1043	3	18.3	1.4	0.2721
Canopy treatment	3	148.5	5.6	0.0057	3	58.8	4.5	0.0463
Cultivar	1	515.9	19.3	0.0003	1	6.1	0.5	0.7075
Treatment × cultivar	3	4.0	0.2	0.9275	3	5.3	0.4	0.7506
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	2	2.8	0.1	0.9272	3	59.9	2.6	0.0781
Canopy treatment	3	103.4	2.8	0.0818	3	182.1	8.0	0.0010
Cultivar	1	719.3	19.5	0.0007	1	1185.3	51.8	<.0001
Treatment × cultivar	3	38.0	1.0	0.4117	3	33.0	1.4	0.2597

Appendix 19

Table 1 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Saskatoon in 2003.

Source of variation	d.f.	Mean Squares	F value	P value	Mean Squares	F value	P value	Mean Squares	F value	P value
		15 DAS†			35 DAS			49 DAS		
Replication	3	2175.4	0.9	0.4439	2165.5	0.6	0.6546	921.3	0.2	0.8751
Cultivar	1	7326.8	3.2	0.0928	12131.6	3.1	0.0962	11298.3	2.8	0.1112
Canopy treatment	3	79.8	0.0	0.9912	1344.1	0.3	0.7957	2493.3	0.6	0.6116
Cultivar × treatment	3	2779.1	1.2	0.3397	4166.8	1.1	0.3913	3549.7	0.9	0.4692
		57 DAS			62 DAS			79 DAS		
Replication	3	537.4	0.1	0.9402	429.1	0.1	0.9588	576.7	0.1	0.9518
Cultivar	1	10436.1	2.6	0.1277	10028.5	2.3	0.1432	11009.7	2.1	0.1605
Canopy treatment	3	2020.0	0.5	0.6912	1845.2	0.4	0.7332	2444.7	0.5	0.7031
Cultivar × treatment	3	3182.9	0.8	0.5216	3023.2	0.7	0.5606	3120.1	0.6	0.6189
		89 DAS								
Replication	3	932.2	0.2	0.9103						
Cultivar	1	13236.4	2.5	0.1299						
Canopy treatment	3	2943.1	0.6	0.6481						
Cultivar × treatment	3	3444.9	0.7	0.5898						

†DAS is days after seeding

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Table 2 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Swift Current in 2003.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		10 DAS†			28 DAS			44 DAS		
Replication	3	220.6	0.6	0.6514	552.1	0.6	0.6069	571.8	0.7	0.5612
Cultivar	1	2.2	0.0	0.9409	0.1	0.0	0.9914	1432.4	1.8	0.2010
Canopy treatment	3	7.2	0.0	0.9965	316.3	0.4	0.7828	461.4	0.6	0.6423
Cultivar × treatment	3	349.3	0.9	0.4711	931.1	1.1	0.3924	293.0	0.4	0.7812
		51 DAS			73 DAS			83 DAS		
Replication	3	554.7	0.7	0.5623	799.6	0.7	0.5957	857.0	0.6	0.6347
Cultivar	1	3029.8	3.9	0.0664	6059.1	4.9	0.0408	5519.9	3.8	0.0696
Canopy treatment	3	1142.0	1.5	0.2632	224.9	0.2	0.9072	539.6	0.4	0.7780
Cultivar × treatment	3	154.3	0.2	0.8977	374.8	0.3	0.8228	343.1	0.2	0.8720

†DAS is days after seeding

Table 3 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Saskatoon in 2004.

Source of variation	d.f.	Mean squares	*F* *value*	*P* *value*	Mean squares	*F* *value*	*P* *value*	Mean squares	*F* *value*	*P* *value*
		35 DAS†			42 DAS			56 DAS		
Replication	3	0.1	0.1	0.9446	14.7	0.8	0.5032	173.9	1.7	0.1986
Cultivar	1	0.3	0.5	0.5065	57.2	3.2	0.0927	1053.5	10.5	0.0048
Canopy treatment	3	1.1	1.6	0.2356	273.5	15.2	<.0001	2335.1	23.3	<.0001
Cultivar × treatment	3	0.3	0.5	0.6960	15.3	0.9	0.4868	63.2	0.6	0.606
		62 DAS			72 DAS			94 DAS		
Replication	3	330.0	2.2	0.1321	567.6	1.9	0.1618	918.4	1.1	0.3840
Cultivar	1	2083.3	13.5	0.0019	3927.7	13.4	0.0019	8018.2	9.4	0.0069
Canopy treatment	3	3125.6	20.3	<.0001	4703.1	16.1	<.0001	9592.1	11.3	0.0003
Cultivar × treatment	3	65.8	0.4	0.7357	84.5	0.3	0.8332	114.9	0.1	0.9377
		114 DAS			134 DAS			158 DAS		
Replication	3	1671.9	1.3	0.3160	3621.3	1.8	0.1781	4723.3	1.9	0.1676
Cultivar	1	14715.8	11.2	0.0038	25356.5	12.9	0.0023	33561.0	13.5	0.0019
Canopy treatment	3	11855.0	9.0	0.0009	15261.6	7.8	0.0018	19050.2	7.7	0.0019
Cultivar × treatment	3	294.0	0.2	0.8788	670.1	0.3	0.7963	856.9	0.4	0.7931

†DAS is days after seeding

Table 4 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Swift Current in 2004.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		16 DAS†			45 DAS			54 DAS		
Replication	3	21.5	1.1	0.3862	10823.2	18.2	<.0001	18262.3	24.0	<.0001
Cultivar	1	36.4	1.8	0.1944	192.6	0.3	0.5761	97.9	0.1	0.7237
Canopy treatment	3	5.4	0.3	0.8464	2098.9	3.5	0.0348	3027.1	4.0	0.0234
Cultivar × treatment	3	31.6	1.6	0.2283	520.6	0.9	0.4715	694.8	0.9	0.453
		60 DAS			68 DAS			80 DAS		
Replication	3	23649.3	29.1	<.0001	30483.8	35.6	<.0001	39034.6	42.3	<.0001
Cultivar	1	43.6	0.1	0.8194	3.0	0.0	0.9535	68.2	0.1	0.7887
Canopy treatment	3	4429.6	5.4	0.0071	8248.5	9.6	0.0004	8159.5	8.8	0.0007
Cultivar × treatment	3	830.9	1.0	0.4054	997.9	1.2	0.3486	1240.7	1.3	0.2898
		102 DAS			123 DAS			140 DAS		
Replication	3	43400.9	41.3	<.0001	39572.6	28.7	<.0001	32847.3	12.8	<.0001
Cultivar	1	635.5	0.6	0.4465	1715.9	1.3	0.2784	2995.8	1.2	0.2940
Canopy treatment	3	7489.8	7.1	0.0021	7333.8	5.3	0.0078	8197.5	3.2	0.0473
Cultivar × treatment	3	1671.5	1.6	0.225	2315.2	1.7	0.205	3164.0	1.2	0.3262

†DAS is days after seeding

Table 5 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Saskatoon in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		20 DAS†			53 DAS			62 DAS		
Replication	2	209.7	0.5	0.6423	732.2	1.2	0.3270	1534.6	2.0	0.1739
Canopy treatment	3	670.3	1.5	0.2489	173.7	0.3	0.5992	7071.1	9.4	0.0099
Cultivar	1	7.6	0.0	0.9969	319.7	0.5	0.6661	1385.9	1.8	0.1946
Treatment × cultivar	3	192.5	0.4	0.7408	196.6	0.3	0.8040	411.4	0.5	0.6611
		70 DAS			79 DAS			89 DAS		
Replication	2	2215.8	2.4	0.1293	3115.2	2.4	0.1297	4596.7	2.1	0.1646
Canopy treatment	3	20302.5	22.3	0.0005	43914.6	34.3	<.0001	77060.8	35.3	<.0001
Cultivar	1	3519.3	3.9	0.0379	4030.7	3.2	0.0648	6156.9	2.8	0.084
Treatment × cultivar	3	856.0	0.9	0.4510	1342.5	1.1	0.4065	2253.8	1.0	0.4132
		108 DAS			145 DAS					
Replication	2	6888.5	1.6	0.2426	9007.4	1.0	0.3910			
Canopy treatment	3	112367.3	26.1	0.0003	232728.0	26.3	0.0003			
Cultivar	1	10940.7	2.5	0.1058	20884.8	2.4	0.1232			
Treatment × cultivar	3	3693.5	0.9	0.4898	7196.9	0.8	0.5114			

†DAS is days after seeding

Table 6 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Swift Current in 2005.

Source of variation	d.f.	Mean squares	F value	P value	Mean squares	F value	P value	Mean squares	F value	P value
		16 DAS†			35 DAS			51 DAS		
Replication	3	3118.2	1.9	0.1632	10432.0	1.8	0.1827	19906.7	2.3	0.1219
Cultivar	1	4114.6	2.6	0.1288	13548.5	2.4	0.1429	28497.8	3.2	0.0916
Canopy treatment	3	210.5	0.1	0.9401	1228.1	0.2	0.8844	13899.8	1.6	0.2354
Cultivar × treatment	3	1701.4	1.1	0.3933	5256.8	0.9	0.453	15612.3	1.8	0.1945
		62 DAS			72 DAS			97 DAS		
Replication	3	21118.5	2.6	0.0911	20351.6	2.7	0.0819	17602.0	2.1	0.1444
Cultivar	1	43174.5	5.2	0.0360	61904.6	8.2	0.0115	100246.7	11.8	0.0034
Canopy treatment	3	24891.6	3.0	0.0604	34889.1	4.6	0.0167	34343.8	4.0	0.0257
Cultivar × treatment	3	18895.9	2.3	0.1169	17020.0	2.2	0.1229	17519.7	2.1	0.1458
		104 DAS			115 DAS					
Replication	3	16970.9	2.0	0.1582	15555.0	2.1	0.1372			
Cultivar	1	95763.1	11.2	0.0042	77110.0	10.5	0.0051			
Canopy treatment	3	33619.6	3.9	0.0285	24117.1	3.3	0.0477			
Cultivar × treatment	3	18341.3	2.1	0.1357	14370.9	2.0	0.1602			

†DAS is days after seeding

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Appendix 20

Table 1 Result from analysis of variance for cumulative intercepted radiation of kabuli chickpea at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	932.2	0.2	0.9103	3	857.0	0.6	0.6347
Cultivar	1	13236.4	2.5	0.1299	1	5519.9	3.8	0.0696
Canopy treatment	3	2943.1	0.6	0.6481	3	539.6	0.4	0.7780
Cultivar × treatment	3	3444.9	0.7	0.5898	3	343.1	0.2	0.8720
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	3	4723.3	1.9	0.1676	3	32847.3	12.8	<.0001
Cultivar	1	33561.0	13.5	0.0019	1	2995.8	1.2	0.2940
Canopy treatment	3	19050.2	7.7	0.0019	3	8197.5	3.2	0.0473
Cultivar × treatment	3	856.9	0.4	0.7931	3	3164.0	1.2	0.3262
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	F value	P value	d.f.	Mean squares	F value	P value
Replication	2	9007.4	1.0	0.3910	3	15555.0	2.1	0.1372
Cultivar	1	20884.8	2.4	0.1232	1	77110.0	10.5	0.0051
Canopy treatment	3	232728.0	26.3	0.0003	3	24117.1	3.3	0.0477
Cultivar × treatment	3	7196.9	0.8	0.5114	3	14370.9	2.0	0.1602

Appendix 21

Table 1 Result from analysis of variance for harvest index of kabuli chickpea at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	0.0043	0.9	0.4611	3	0.0004	0.5	0.7067
Canopy treatment	3	0.0021	0.4	0.7280	3	0.0030	3.6	0.0329
Cultivar	1	0.0061	1.3	0.2743	1	0.0257	31.3	<.0001
Treatment × cultivar	3	0.0007	0.2	0.9301	3	0.0022	2.6	0.0792
Source of variation	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	0.0109	1.8	0.1765	3	0.1400	38.9	<.0001
Canopy treatment	5	0.0083	1.3	0.2754	5	0.0227	6.3	0.0003
Cultivar	1	0.1548	24.8	<.0001	1	0.0065	1.8	0.1895
Treatment × cultivar	5	0.0020	0.3	0.8964	5	0.0016	0.4	0.8188
Source of variation	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	2	0.0220	6.9	0.0051	3	0.0006	0.3	0.8522
Canopy treatment	5	0.0082	2.6	0.0583	5	0.0085	4.0	0.0060
Cultivar	1	0.8006	249.8	<.0001	1	0.0463	21.7	<.0001
Treatment × cultivar	5	0.0047	1.5	0.2463	5	0.0036	1.7	0.1610

Appendix 22

Table 1 Result from analysis of variance for yield of kabuli chickpea at Saskatoon and Swift Current in 2003, 2004 and 2005.

Source of variation	2003 Saskatoon				2003 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	480722.4	12.6	<.0001	3	34649.3	1.3	0.3155
Canopy treatment	3	141098.4	3.7	0.0278	3	29365.4	1.1	0.3859
Cultivar	1	87048.8	2.3	0.1456	1	10731.1	0.4	0.5398
Treatment × cultivar	3	8278.8	0.2	0.8834	3	433.4	0.0	0.9972
	2004 Saskatoon				2004 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	3	493605.9	6.5	0.0014	3	3000162.1	17.6	<.0001
Canopy treatment	5	438913.5	5.8	0.0006	5	2136776.3	12.5	<.0001
Cultivar	1	2526267.8	33.2	<.0001	1	216248.9	1.3	0.2682
Treatment × cultivar	5	95756.4	1.3	0.3054	5	79823.4	0.5	0.7967
	2005 Saskatoon				2005 Swift Current			
	d.f.	Mean squares	*F* value	*P* value	d.f.	Mean squares	*F* value	*P* value
Replication	2	2249335.9	0.9	0.4261	3	267075.1	1.3	0.2941
Canopy treatment	5	3269732.0	1.3	0.3049	5	350337.3	1.7	0.1640
Cultivar	1	49145158.5	19.4	0.0002	1	3737484.1	18.1	0.0002
Treatment × cultivar	5	2789114.5	1.1	0.3889	5	124390.7	0.6	0.6996