Interrelationships among yield components of chickpea in semiarid environments

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Gan, Y. T., Liu, P. H., Stevenson, F. C. and McDonald, C. L. 2003. **Interrelationships among yield components of chickpea in semiarid environments.** Can. J. Plant Sci. **83**: 759–767. Chickpea (*Cicer arietinum* L.) seed yield can be increased by identifying and managing the key yield components. A field study was conducted in southwestern Saskatchewan in 1999 and 2000 to determine the direct and indirect effects of various yield components on chickpea seed yield. Both desi- and kabuli-chickpea were planted at the target plant populations of 20, 30, 40, and 50 plants m^{-2} on conventional summerfallow (CS) and no-till wheat stubble (NT). Path coefficient analyses revealed that seed yield for both chickpea classes largely depended upon pods m^{-2} and seed weight, with the kabuli crop having higher coefficient values than the desi. These relationships were stronger when the pulses were grown on CS than on NT. Seeds pod^{-1} had a negative effect on seed yield for the kabuli crop, but this negative effect was counterbalanced by a strong, positive effect of seed weight on seed yield. The total pod production of the desi crop depended on plants m^{-2} more than on pods $plant^{-1}$, whereas the pod production of the kabuli crop relied equally on plants m^{-2} and pods $plant^{-1}$. For both chickpea classes, mean seed weight decreased with prolonged vegetative growth period regardless of tillage environment. Seed weight was positively related to the length of reproductive growth and seeds pod^{-1} only when the pulses were grown on CS. Seed yield potential of desi chickpea would be increased by increasing plant population to produce more pods per unit area, whereas the seed yield potential of kabuli chickpea would be increased by shortening the period of vegetative growth, promoting the number of pods per plant, and increasing mean seed weight.

Key words: *Cicer arietinum*, yield components, plant density, seed weight, canopy, path analysis

Gan, Y. T., Liu, P. H., Stevenson, F. C. et McDonald, C. L. 2003. **Relations entre les composantes du rendement chez le pois chiche cultivé en milieu semi-aride**. Can. J. Plant Sci. **83**: 759–767. On peut accroître le rendement grainier du pois chiche (*Cicer arietinum* L.) en identifiant et en gérant les principales composantes du rendement. Les auteurs ont entrepris une étude sur le terrain dans le sud-ouest de la Saskatchewan en 1999 et 2000 afin de préciser l'incidence directe et indirecte de divers facteurs sur le rendement grainier du pois chiche. Pour cela, ils ont planté des pois chiches de type desi et kabuli à une densité de 20, 30, 40 et 50 plants par m^2 sur de la jachère d'été ordinaire (CS) et du chaume de blé sans travailler le sol (NT). L'analyse des coefficients de dépendance révèle que, dans les deux cas, le rendement grainier dépend largement du nombre de gousses par m^2 et du poids des semences, le pois kabuli se caractérisant par des coefficients d'une valeur supérieure à celle du pois desi. Ces relations sont plus étroites quand les légumineuses sont cultivées sur CS plutôt que sur NT. Le nombre de graines par gousse a une incidence négative sur le rendement grainier du pois kabuli, mais elle est compensées par la forte incidence positive du poids des semences sur le rendement grainier. La production totale de gousses par le pois desi dépend plus du nombre de plants au m^2 que du nombre de gousses par plant alors que pour le pois kabuli, elle dépend autant des deux facteurs. Pour le pois desi comme le pois kabuli, le poids moyen des graines diminue quand la croissance végétative se prolonge, que le sol ait été travaillé ou pas. Le poids des semences ne présente une corrélation positive avec la durée de la période reproductive et le nombre de graines par gousse que lorsqu'on cultive les légumineuses sur CS. On pourrait améliorer le rendement grainier potentiel du pois desi en augmentant la densité du peuplement pour obtenir plus de gousses par unité de surface, mais pour améliorer le rendement potentiel du pois kabuli, il faudrait raccourcir la croissance végétative, accroître le nombre de gousses par plant et relever le poids moyen des semences.

Mots clés: *Cicer arietinum*, composantes du rendement, densité de peuplement, poids des graines, couvert, analyse des coefficients de dépendance

Emphasis on soil health, environmental quality, and economic innovation has stimulated significant changes in cropping systems throughout the Canadian prairies where the dryland crop production has traditionally been annual cereals, namely spring wheat (*Triticum aestivum* L.) and durum wheat (*Triticum turgidum* L.). Producers are seeking alternate cropping systems to increase their economic returns (Miller et al. 2002). Chickpea, an annual grain legume, is an alternative to cereals in the drier areas of southwestern Saskatchewan and southeastern Alberta (Gan and Noble 2000). The areas seeded to chickpea in these regions have increased from <6000 ha in 1995 to >400 000 ha in 2001.

In commercial production of chickpea, the cost of seed is the major input expense, often exceeding Can\$140 to \$180 ha^{-1}, which accounts for approximately 40% of the total production inputs. Use of a low seeding rate would reduce production costs, but a thin crop population may reduce seed yield. Gan et al. (2003) found under CS or NT,

Abbreviations: **CS**, conventional summerfallow; **NT**, no-till wheat stubble; **PPD**, plant population density increased population densities increased chickpea seed yield, although in a dry year no response to increased population was found on NT. Gan et al. (2003) did not report detailed seed yield components, nor the interrelationships between yield components and seed yield. It is not known how chickpea plants adjust their ontogenetic characteristics to maximize seed yield when grown under different plant population densities. Information on the relative importance of various yield components to seed yield is useful for producers to manage the crop by focusing on key yield components. This type of information is also useful for chickpea breeders to establish selection criteria in genetic manipulation. For example, selection for high-yielding cultivars through specific traits requires knowledge not only on the mechanisms of seed yield formation but also on the physiological processes relative to setting pods (Egli and Yu 1991), forming the seed number (Board and Tan 1995), and filling these potential fruiting sites (Ball et al. 2001).

Statistical correlations usually exist among morphological characteristics, grain yield, and the principal components in grain crops (Gebeyehou et al.1982; Garcia del Moral et al. 1991). Correlation analyses usually provide a general representation of the relative influence of individual characteristics or variables on final yield. Seed yield components of annual legumes such as soybeans (*Glycine max* L.) and chickpeas are formed during the successive phases of plant development (Board et al. 1999; Ball et al. 2001). The final seed mass of these legumes can be influenced directly or indirectly by ontogenetic traits developed in an earlier growth stage (such as germination, plant establishment, and vegetative growth periods) and also by the traits developed in the later part of the growing season (such as number of seeds per pod and seed weight). Our lack of knowledge of yield component compensation remains one of the impediments to progress in determining factors that influence final seed mass in chickpea.

Path coefficient analysis, developed originally by Wright (1921) and elaborated later by Dewey and Lu (1959), has been used to partition correlation coefficients into direct and indirect effects of each yield component or yield-related variable to grain yield. Path analysis is based on the assumption of mutual relationships among yield components. Statistically, path coefficients are standardized partial-regression coefficients, obtained from equations where the yield-related variables are expressed as deviations from the means in units of standard deviation (Steel et al. 1997). Path analysis has been used in agronomic research for crops such as crested wheatgrass (*Agropyron desertorum* F.) (Dewey and Lu 1959), spring wheat (Gebeyehou et al. 1982), spring barley (*Hordeum vulgare* L.) (Pury et al. 1982; Garcia del Moral et al. 1991), field bean (*Phaseolus vulgaris* L.) (Duarte and Adams 1972), and soybean (Board et al. 1999; Ball et al. 2001). This method has been used to determine the interrelationships between grain production and biomass, leaf area index, and the effect of environmental conditions on yield components (Campbell et al. 1980; Ramos et al. 1989). In the published studies, seed production and yield components are regarded as a system of interrelated variables, with yield components considered at the same ontogenetic level.

The objectives of our study were to determine for chickpea grown on the semiarid Canadian prairies (i) the relative importance of various yield components to final seed mass, and (ii) the relationships among seed yield, yield components, and the length of pre-anthesis and seed-filling periods.

MATERIALS AND METHODS

The field experiment was conducted in 1999 and 2000 at two sites in southwestern Saskatchewan. The first site was on an Orthic Brown Chernozem with loam to silt loam texture and a saturated-paste pH of 6.5 in the 0- to 15-cm depth (Ayers et al. 1985). This site was at the Agriculture and Agri-Food Canada Semiarid Prairie Agricultural Research Centre near Swift Current (50.2°N 107.4°W). The second site was on a Rego Brown Chernozem with heavy clay texture and a saturated-paste pH of 6.8 in the 0- to 15-cm depth (Ayers et al. 1985) on a farmer's field near Stewart Valley (50.6°N, 107.4°W).

Experiment Design and Plot Management

The treatments consisted of three factors: (i) chickpea market class, (ii) plant population density (PPD), and (iii) field phase (i.e., conventional summerfallow and no-till wheat stubble). Two market classes of chickpea, kabuli (cvs. CDC Xena and CDC Yuma) and desi (cv. Myles), were planted at four seeding rates to obtain the target PPD of 20, 30, 40, and 50 plants m^{-2} (Table 1). The seeding rates were based on seed size, pre-seed germination, and an estimated field emergence rate of 75%. Chickpea market class and PPD were arranged in a factorial, randomized complete block with four replicates. The experiment was conducted on conventional summerfallow and no-till wheat stubble. The two field phases were established side-by-side in the field, for ease of field operations.

Prior to planting, seed was treated using the methods described by Hwang et al. (2000). Plots were seeded at a depth of 5 to 6 cm on 7 May 1999 and 2 May 2000 at Swift Current, and on 20 May 1999 and 5 May 2000 at Stewart Valley. At planting, noon soil temperature at a 10-cm depth was between 9 and 13°C. The various rates of seeding were accomplished with a 2-m-wide hoe press drill equipped with a spinner seed metre. Each plot was 7.5 m long, consisting of eight rows with a 25-cm row spacing. Monoammonium phosphate was applied with the seed at a rate of 7.5 kg P ha^{-1}. All plots received 5.5 kg ha^{-1} of Nitragin (Lipha Tech Inc. Saskatoon, SK, Canada), an appropriate soil implant *Rhizobium* inoculant (a granular form) for symbiotic N fixation. The *Rhizobium* inoculant was applied in the seed rows. Weeds were controlled with appropriately labeled herbicides to minimize overall weed pressure. All plots were sprayed with chlorothalonil (Syngenta, Canada) at the recommended rate to control Ascochyta blight, a foliar disease caused by *Ascochyta rabiei*.

After seedling emergence was complete, we conducted plant counts in two 0.5-m^2 quadrants; one in the front and the other in the back of the plot. Phenological stages of the plants were recorded based on the Universal Growth Staging

Table 1. Kabuli- and desi-chickpea were planted at four population densities in southwestern Saskatchewan, in 1999 and 2000

Year	Class Type	Cultivar	Seed weight (g seed $^{-1}$)	Seed germination (%)	Target plant population density (plants m^{-2})[z] 20	30	40	50
					Actual plant population density (plants m^{-2})[z]			
1999	Kabuli	CDC Xena	500	96	18(1.0)	32 (1.2)	37 (1.4)	48 (2.2)
	Kabuli	CDC Yuma	370	96	20 (1.2)	32 (1.2)	39 (1.3)	48 (2.2)
	Desi	Myles	180	98	17 (1.3)	30 (1.7)	38 (1.9)	46 (1.5)
2000	Kabuli	CDC Xena	466	98	26 (5.0)	35 (4.0)	44 (2.1)	50 (2.6)
	Kabuli	CDC Yuma	370	98	26 (2.2)	34 (1.3)	40 (1.4)	51 (2.7)
	Desi	Myles	192	96	22 (2.7)	32 (2.1)	40 (2.0)	48 (3.2)

[z]Means of Swift Current and Stewart Valley sites as there was no significant difference between the two. The numbers in parentheses are SEs.

Table 2. *P* values from analysis of variance, showing the interactions among plant density, crop type, and site for the yield-related variables of chickpea grown on conventional summerfallow (CS) and on no-till wheat stubble (NT), in southwest Saskatchewan, 1999 and 2000

Effect	Plants m^{-2}	Vegetative period (d)	Pods plant^{-1}	Reproductive period (d)	Pods m^{-2}	Seeds pod^{-1}	Seed weight (mg seed^{-1})	Seed yield (kg ha^{-1})
CS								
Density (D)	< 0.01	0.05	0.01	0.35	0.05	0.07	0.31	0.01
Cultivar (C)	0.28	0.21	0.06	0.79	0.05	0.45	0.01	0.82
C × D	0.59	0.49	0.83	0.69	0.68	0.12	0.45	0.30
Site (S)	0.15	0.17	0.44	0.19	0.25	0.47	0.38	0.17
S × D	0.39	–[z]	0.22	0.30	–	0.11	–	0.35
S × C	–	0.12	0.16	0.12	0.17	0.19	0.16	0.15
S × C × D	–	0.21	0.46	0.37	–	–	0.04	–
NT								
Density (D)	< 0.01	0.01	0.01	0.23	0.31	0.54	0.45	0.01
Cultivar (C)	0.89	0.20	< 0.01	0.76	< 0.01	0.73	< 0.01	0.86
C × D	0.49	0.36	0.01	0.98	0.20	0.53	0.18	0.01
Site (S)	0.14	0.17	0.16	0.22	0.15	0.23	0.25	0.15
S × D	–	–	0.48	0.38	–	0.30	0.29	–
S × C	0.36	0.12	–	0.12	–	0.23	0.46	0.21
S × C × D	0.41	–	–	–	–	0.12	–	0.41

[z]Variance component estimate was 0.

Table 3. *P* values from analysis of variance, showing the interactions between plant density and site for the yield-related variables of chickpea grown on conventional summerfallow (CS) and no-till wheat stubble (NT) in southwest Saskatchewan, 1999 and 2000

Effect	Plants m^{-2}	Vegetative period (d)	Pods plant^{-1}	Reproductive period (d)	Pods m^{-2}	Seeds pod^{-1}	Seed weight (mg seed^{-1})	Seed yield (kg ha^{-1})
CS								
Desi								
Density (D)	< 0.01	0.93	< 0.01	< 0.01	0.22	0.76	0.87	< 0.01
Site (S)	0.18	0.18	0.22	0.15	0.3	0.29	0.29	0.16
S × D	–[z]	0.4	–	–	–	0.44	0.18	
Kabuli								
Density (D)	< 0.01	0.23	< 0.01	0.35	0.15	0.06	0.58	0.01
Site (S)	0.15	0.17	0.16	0.12	0.15	0.31	0.32	0.15
S × D	0.38	–	–	0.48	–	0.15	–	0.48
NT								
Desi								
Density (D)	< 0.01	0.21	0.01	< 0.01	0.03	0.39	0.88	0.01
Site (S)	0.15	0.19	0.33	0.16	0.39	–	0.25	0.22
S × D	–	–	0.14	–	–	0.39	0.05	0.41
Kabuli								
Density (D)	< 0.01	0.12	< 0.01	0.27	0.46	0.41	0.77	0.01
Site (S)	0.13	0.16	0.17	0.13	0.17	0.16	0.24	0.14
S × D		–	–	–	–	0.19	–	–

[z]Variance component estimate was 0.

Scales described by Lancashire et al. (1991). The calendar date was recorded for seedling emergence (when 50% of the seedlings had emerged based on a visual count), anthesis (when 50% of the plants in a plot were blooming), and maturity (when seed moisture reached 300 to 350 g kg^{-1}). Ten individual plants were sampled at random from each plot at maturity for yield component determination. In the laboratory, we opened all pods on the 10 individual plants by hand and counted the number of pods $plant^{-1}$ and the number of seeds pod^{-1}. Number of pods per unit area was calculated as plant population density multiplied by pods per plant. Data from the 10 individual plants were averaged for each plot. The centre six rows of each plot (7.0 m^2) were harvested with a plot combine when the crop had dried sufficiently for satisfactory threshing. The seed samples were cleaned, air-dried, and weighed. Seed yields per unit area were presented on a moisture concentration of 50 g kg^{-1}. A subsample was taken from the dried grain sample and mean seed weight was determined based on two, 500 seed assessments.

Statistical Analysis

Data were analyzed with the PROC MIXED procedure of SAS software (Littel et al. 1996). The first analysis was conducted separately for each field phase and included block and site-year as random effects, and chickpea cultivar and PPD as fixed effects. The two kabuli cultivars, CDC Xena and CDC Yuma, often responded to treatments similarly (Table 2). Therefore, the average responses across the two kabuli cultivars was used for subsequent analyses.

The second analysis was conducted separately for each chickpea market class and field phase and included block and site-year as random effects, and PPD as a fixed effect. The analysis revealed that site-year × treatment interactions, with few exceptions, were not significant for the response variables measured in the study (Table 3). The results from the analysis of variance indicated that variation among sites was negligible. Therefore, succeeding analyses were conducted for pooled data across the 4 site-years. Moreover, our objective was to determine the relationships among yield components across environmental conditions on the semiarid Canadian prairies.

Path diagram (Fig. 1) described the interrelationships among the variables used in the study. These cause-effect systems were based on the ontogeny of the growth habit of chickpea. The number of pods $plant^{-1}$ and the length of vegetative growth have a mutual relationship (double-headed arrows), as both characteristics may exercise a reciprocal influence during the early growth stages under normal conditions. The length of reproductive growth (from anthesis to maturity) was included in the logic, based on previous findings (Gan et al. 2002) that a prolonged reproductive phase in chickpea increases heat unit accumulation for pod setting and seed formation. Early pod set through shortening the reproductive period or early flowering in chickpea has been recognized as a prime strategy for avoiding drought stress in semiarid environments prone to end-of-season moisture stress (Kumar and Abbo 2001).

Correlation and path analyses were conducted for (1) PPD, (2) vegetative period (from seedling emergence to anthesis), (3) number of pods per plant, (4) grain-filling period (from anthesis to maturity), (5) number of pods per unit area, (6) number of seeds per pod, (7) mean weight per seed, and (8) seed yield. Correlation coefficients were calculated separately for each chickpea market class and field phase (Tables 4 and 5). Then, path analysis, similar to that used by Garcia del Moral et al. (1991) and Ball et al. (2001), was used to determine the direct and indirect effects of plant characteristics and/or yield-related variables on seed yield (Table 6), pod production (Table 7) and seed weight (Table 8). In these analyses, correlation coefficients were partitioned into direct and indirect effects by solving the following sets of equations simultaneously:

$$r_{58} = P_{58} + r_{56}P_{68} + r_{57}P_{78}$$
$$r_{68} = r_{56}P_{58} + P_{68} + r_{67}P_{78}$$
$$r_{78} = r_{57}P_{58} + r_{67}P_{68} + P_{78}$$

$$r_{37} = r_{43}P_{47} + P_{37} + r_{36}P_{67}$$
$$r_{47} = P_{47} + r_{43}P_{37} + r_{46}P_{67}$$
$$r_{67} = r_{46}P_{47} + r_{36}P_{37} + P_{67}$$

$$r_{15} = P_{15} + r_{13}P_{35}$$
$$r_{35} = r_{13}P_{15} + P_{35}$$

$$r_{16} = P_{16} + r_{14}P_{46} + r_{13}P_{36} + r_{15}P_{56}$$
$$r_{36} = r_{13}P_{16} + P_{36} + r_{34}P_{46} + r_{35}P_{56}$$
$$r_{46} = r_{14}P_{16} + r_{34}P_{36} + P_{46}$$
$$r_{56} = r_{15}P_{16} + r_{35}P_{36} + P_{56}$$

$$r_{14} = P_{14} + r_{12}P_{24}$$
$$r_{24} = r_{12}P_{14} + P_{24}$$

$$r_{34} = r_{14}P_{13} + P_{34}$$
$$r_{13} = P_{13} + r_{14}P_{34}$$

In the equation of $r_{15} = P_{15} + r_{13}P_{35}$, r_{15} is the correlation coefficient between variable 1 (plant density in Fig. 1) and variable 5 (pods m^{-2} in Fig. 1), the P_{15} is the path coefficient for the direct effect of variable 1 on variable 5, and $r_{13}P_{35}$ is the indirect effect of variable 1 on variable 5 via variable 3 (pods $plant^{-1}$ in Fig. 1). Similar definitions apply to the rest of the equations. Test for significance of path coefficients was achieved by testing for partial regression coefficient.

RESULTS AND DISCUSSION

Weather conditions differed from long-term averages in both years. In 1999, cool and wet conditions occurred during the entire growing season, with total precipitation being 15% higher than normal (204 mm) and air temperature being 0.8°C (or 6%) lower than normal (15.6°C). The favourable moisture conditions in 1999 promoted a long period for vegetative growth in chickpea, but the low temperatures limited seed yield potential. In 2000, temperatures in late July to early August were higher than normal, promoting pod set and seed fill in chickpea.

In both years, good plant establishment was achieved for all treatments (Table 1), and the crop reached physiological

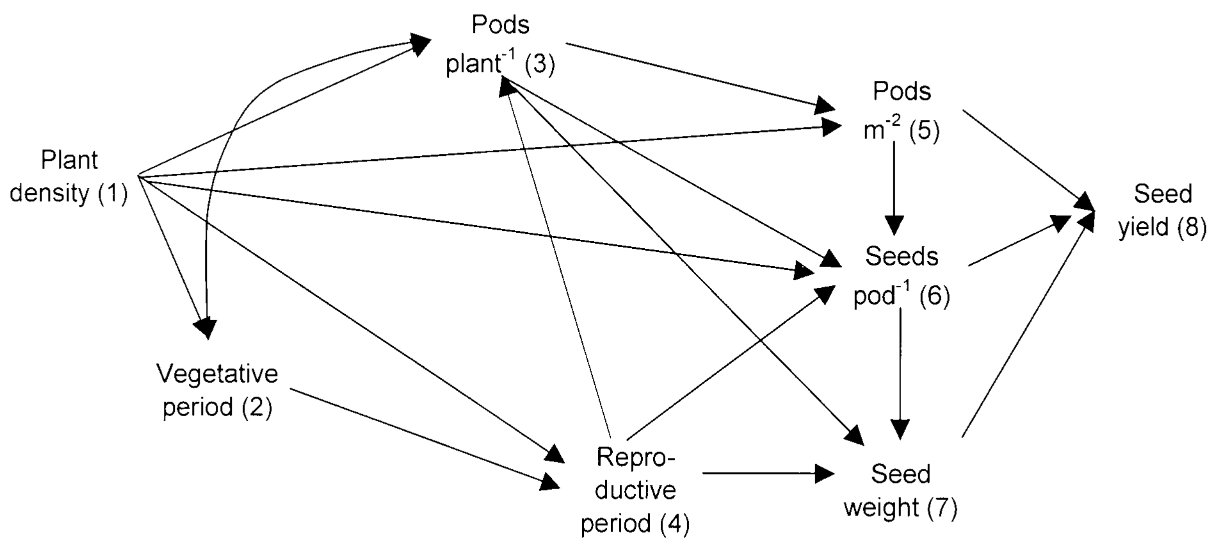

Fig. 1. Pathways showing the cause–effect relationships among yield components and their effects on seed yield of chickpea grown in a semiarid environment of southwestern Saskatchewan, 1999–2000.

Table 4. Simple correlation coefficients for yield and yield–related variables for desi-chickpea grown on conventional summerfallow (CS, below diagonal) and no-tilled wheat stubble (NT, above diagonal) at Swift Current and Stewart Valley, SK, in 1999 and 2000

Variables	Plants m^{-2}	Vegetative period (d)	Pods $plant^{-1}$	Reproductive period (d)	Pods m^{-2}	Seeds pod^{-1}	Seed weight (g $seed^{-1}$)	Seed yield (kg ha^{-1})
					NT			
Plants m^{-2}	–	–0.12	–0.64**	–0.04	0.66**	–0.15	–0.02	0.48**
Vegetative period (d)	–0.12	–	–0.14	–0.46**	–0.25	–0.10	–0.79**	–0.59**
Pods $plant^{-1}$	–0.69**	–0.08	–	0.18	0.08	–0.10	0.22	–0.33
Reproductive period (d)	–0.04	–0.69*	0.04	–	0.14	0.16	0.14	0.26
Pods m^{-2}	0.38**	–0.24	0.31*	–0.05	–	–0.16	0.12	0.28*
Seeds pod^{-1}	–0.15	–0.38**	0.11	0.12	–0.04	–	0.1	–0.09
Seed weight (g $seed^{-1}$)	0.06	–0.92**	0.09	0.57**	0.17	0.42**	–	0.36**
Seed yield (kg ha^{-1})	0.53**	–0.63**	–0.19	0.24	0.44**	0.04	0.51**	–
					CS			

*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 5. Simple correlation coefficients for yield and yield-related variables for kabuli-chickpea grown on conventional summerfallow (CS, below diagonal) and no-tilled wheat stubble (NT, above diagonal) at Swift Current and Stewart Valley, SK, in 1999 and 2000

Variables	Plants m^{-2}	Vegetative period (d)	Pods $plant^{-1}$	Reproductive period (d)	Pods m^{-2}	Seeds pod^{-1}	Seed weight (g $seed^{-1}$)	Seed yield (kg ha^{-1})
					NT			
Plants m^{-2}	–	< 0.01	–0.63**	0.02	0.37**	–0.34**	< 0.01	0.31**
Vegetative period (d)	0.01	–	–0.03	–0.41**	–0.08	–0.05	–0.56**	–0.34**
Pods $plant^{-1}$	–0.62**	–0.05	–	–0.03	0.42**	0.16	–0.06	0.04
Reproductive period (d)	0.05	–0.60**	–0.07	–	< 0.01	–0.32**	0.12	–0.01
Pods m^{-2}	0.39**	–0.15	0.41**	0.09	–	–0.20*	–0.07	0.35**
Seeds pod^{-1}	–0.50**	–0.20*	0.29**	–0.6	–0.14*	–	0.02	–0.07
Seed weight (g $seed^{-1}$)	–0.06	–0.63**	–0.06	0.15	–0.14	0.27**	–	0.47**
Seed yield (kg ha^{-1})	0.29**	–0.42**	–0.09	–0.13	0.51**	–0.08	0.49**	–
					CS			

*, ** Significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

maturity prior to the first killing frost at each site-year. The period from anthesis to maturity lasted an average of 41 to 46 d, during which new pods continuously emerged, with the early-emerged pods being in the seed-filling process. Therefore, the length of reproductive period might have modified pods $plant^{-1}$ and seeds pod^{-1}. The mean seed weight depended on the duration of the reproductive period, pods $plant^{-1}$, and seeds pod^{-1}. Production of primary and

Table 6. Path coefficient analysis for seed yield (kg ha^{-1}) of desi- and kabuli-chickpea grown on conventional summerfallow (CS) and no-till wheat stubble (NT) in Swift Current and Stewart Valley, SK, in 1999 and 2000

	Desi		Kabuli	
Pathway[z]	CS	NT	CS	NT
Multiple *r*	0.644	0.424	0.772	0.632
Pods m^{-2} vs. seed yield				
Correlation (r_{58})[y]	0.439**	0.284*	0.505*	0.345**
Direct effect (P_{58})[y]	0.343**	0.222*	0.567*	0.379**
Indirect effect via				
seeds pod^{-1} ($r_{56}P_{68}$)	0.007	0.014	0.024	0.001
seed weight ($r_{57}P_{78}$)	0.089	0.038	–0.085	–0.035
Seeds pod^{-1} vs. seed yield				
Correlation (r_{68})	0.04	–0.089	–0.082	–0.068
Direct effect (P_{68})	–0.164	–0.087	–0.171*	–0.003
Indirect effect via				
pods m^{-2} ($r_{56}P_{58}$)	–0.015	–0.035	–0.08	–0.076
seed weight ($r_{67}P_{78}$)	0.219	0.031	0.167	0.011
Seed weight vs. seed yield				
Correlation (r_{78})	0.514**	0.361**	0.493**	0.473**
Direct effect (P_{78})	0.526**	0.315*	0.610**	0.531**
Indirect effect via				
pods m^{-2} (*r*57P58)	0.058	0.027	–0.079	–0.025
seeds pod^{-1} ($r_{67}P_{68}$)	–0.069	–0.009	–0.047	–0.0001

[z]The *r* and *P* refer to path coefficient analysis of direct and indirect effects among yield components or variables indicated by subscripts: 1 = plants m^{-2}, 2 = vegetative period (d), 3 = pods plant^{-1}, 4 = reproductive period (d), 5 = pods m^{-2}, 6 = seeds pod^{-1}, 7 = seed weight (g seed^{-1}), and 8 = seed yield (kg ha^{-1}).
[y]r_{58}, and P_{58} refer to correlation coefficient, and path coefficient between variable 5 and 8, respectively. The same definitions apply to the other coefficients.
*, ** Significant at $P \le 0.05$, and $P \le 0.01$, respectively.

Table 7. Path coefficient analysis for pod production of desi- and kabuli-chickpea grown on conventional summerfallow (CS) and no-till wheat stubble (NT) in Swift Current and Stewart Valley, SK, in 1999 and 2000

	Desi		Kabuli	
Pathway[z]	CS	NT	CS	NT
Multiple *r*	0.888	0.923	0.925	0.913
Plants m^{-2} vs. pods m^{-2}				
Correlation (r_{15})[y]	0.381**	0.658**	0.391**	0.367**
Direct effect (P_{15})[y]	1.150**	1.253**	1.065**	1.048**
Indirect effect via				
pods plant^{-1} ($r_{13}P_{35}$)	–0.769	–0.58	–0.649	–0.681
Pods plant^{-1} vs. pods m^{-2}				
Correlation (r_{35})	0.315*	0.078	0.413**	0.416**
Direct effect (P_{35})	1.111**	0.902**	1.049**	1.078**
Indirect effect via				
plants m^{-2} ($r_{13}P_{15}$)	–0.796	–0.806	–0.659	–0.662

[z]The *r* and *P* refer to path coefficient analysis of direct and indirect effects among yield components or variables indicated by subscripts: 1 = plants m^{-2}, 2 = vegetative period (d), 3 = pods plant^{-1}, 4 = reproductive period (d), 5 = pods m^{-2}, 6 = seeds pod^{-1}, 7 = seed weight (g seed^{-1}), and 8 = seed yield (kg ha^{-1}).
[y]r_{15}, and P_{15} refer to correlation coefficient, and path coefficient between variable 1 and 5, respectively. The same definitions apply to the other coefficients.
*, ** Significant at $P \le 0.05$ and $P \le 0.01$, respectively.

secondary branches is one of the earlier developmental processes in chickpea, and for this reason the pods per unit area exercised a direct influence on all yield components formed in the later part of the development stages.

Seed Yield

The overall effects of PPD on chickpea seed yield have been reported elsewhere (Gan et al. 2003). In brief, seed yield increased linearly with increasing PPD when chickpea was grown on CS. The PPD that produced the highest seed yield ranged from 40 to 45 plants m^{-2} for kabuli chickpea, and from 45 to 50 plants m^{-2} for the desi. When the legumes were no-till planted on wheat stubble, the PPD that produced highest seed yield ranged from 35 to 40 plants m^{-2} for kabuli chickpea, and from 40 to 45 plants m^{-2} for the desi. Increases of seed yield with increasing PPD were more pronounced for chickpea grown on CS compared to when grown on NT wheat stubble. Under the semiarid conditions, greater soil moisture available with CS promoted more primary and secondary branches with fertile pods.

Seed yield of desi chickpea grown on CS or NT was positively correlated with PPD, pods m^{-2}, and seed weight, and was negatively correlated with the length of vegetative period (Table 4). Similar correlations of other traits existed for the desi class grown on CS (coefficients shown below the diagonal of Table 4) and when grown on NT (coefficients shown above the diagonal of Table 4). Kabuli chickpea had somewhat similar correlations between yield components and seed yield (Table 5). Overall, number of pods per unit area had the greatest effect on seed yield among the eight yield-related variables examined in this study (Tables 4 and 5).

Path coefficient analyses provided a more complete picture of the effects of yield components on seed yield, as path coefficients partitioned correlation coefficients into direct and indirect effects. Seed yield of desi chickpea largely depended upon both pods m^{-2} and seed weight, but was not related to seeds pod^{-1} (Table 6). Worth noting were the stronger relationships (greater path coefficient value) between pods m^{-2} and seed yield for the desi crop grown on CS compared to NT. Most of the indirect effects on desi seed yield were not significant regardless of growing environment. The indirect path coefficient for seeds pod^{-1} on seed yield through seed weight was seven times greater for the desi grown on CS ($r_{67}P_{78} = 0.22$) compared to NT ($r_{67}P_{78} = 0.03$) (although not significant). Better soil moisture on CS in the later part of the growing season probably promoted the translocation of photosynthate from vegetative tissues to the fruit sites, increasing seed size and compensating for the negative effect of seeds pod^{-1} on seed yield.

Compared to desi, the kabuli class had stronger interrelationships between yield components and seed yield in most cases (Table 6). Kabuli seed yield mainly depended upon the number of pods per unit area, and secondly upon seed weight, with the coefficient values being greater than those found for desi crop. Similar relationships between yield-related variables and seed yield were found for chickpea grown under the different growing environments, except the kabuli grown on CS where there was a small, but significant, direct effect of seeds pod^{-1} on seed yield (Table 6). This negative effect of seeds pod^{-1} on seed yield for the kabuli grown on CS was compensated by the

Table 8. Path coefficient analysis for mean seed weight (g seed^{-1}) of desi- and kabuli-chickpea grown on conventional summerfallow (CS) and no-till wheat stubble (NT) in Swift Current and Stewart Valley, SK, in 1999 and 2000

Pathway[z]	Desi		Kabuli	
	CS	NT	CS	NT
Multiple *r*	0.685	0.277	0.316	0.132
Pods plant^{-1} vs. seed weight				
Correlation (r_{37}) [y]	0.095	0.217	–0.061	–0.064
Direct effect (P_{37}) [y]	0.033	0.222	–0.174	–0.072
Indirect effect via				
reproductive period ($r_{34}P_{47}$)	0.025	0.021	0.012	–0.003
seed pod^{-1} ($r_{36}P_{67}$)	0.037	–0.007	0.099	0.012
Reproductive period vs. seed weight				
Correlation (r_{47})	0.574**	0.138	0.152	0.12
Direct effect (P_{47})	0.546**	0.117	0.181**	0.118
Indirect effect via				
pods plant^{-1} ($r_{34}P_{37}$)	0.001	0.04	–0.012	0.002
seeds pod^{-1} ($r_{46}P_{67}$)	0.042	0.011	–0.019	–0.023
Seeds pod^{-1} vs. seed weight				
Correlation (r_{67})	0.417**	0.098	0.273**	0.021*
Direct effect (P_{67})	0.348**	0.069	0.339*	0.071
Indirect effect via				
pods plant^{-1} ($r_{36}P_{37}$)	0.004	–0.023	–0.051	–0.012
reproductive period ($r_{46}P_{47}$)	0.065	0.019	–0.01	–0.038

[z]The *r* and *P* refer to path coefficient analysis of direct and indirect effects among yield components or variables indicated by subscripts: 1 = plants m^{-2}, 2 = vegetative period (d), 3 = pods plant^{-1}, 4 = reproductive period (d), 5 = pods m^{-2}, 6 = seeds pod^{-1}, 7 = seed weight (g seed^{-1}), and 8 = seed yield (kg ha^{-1}).
[y]r_{37}, and P_{37} refer to correlation coefficient, and path coefficient between variable 3 and 7, respectively. The same definitions apply to the other coefficients.
*, **Significant at $P \leq 0.05$, and $P \leq 0.01$, respectively.

large, positive direct effects of pods m^{-2} and seed weight on seed yield.

Pod Production

Path coefficients revealed that total pod production depended directly on plant population density and the number of pods per plant in both desi and kabuli chickpea (Table 7). Total pod production relied on plants m^{-2} more than on pods plant^{-1} for desi chickpea, whereas the total pod production of kabuli plants depended equally on pods plant^{-1} and plants m^{-2}. The growing environment (i.e., CS and NT) did not alter these associations. In all situations, there were negative indirect effects of plants m^{-2} on total pod production through pods plant^{-1} ($r_{13}P_{35}$ = –0.58 to –0.77), but this negative indirect effect was counterbalanced by the strong, positive direct effects of plants m^{-2}. Similarly, there was a negative indirect effect of pods plant^{-1} on the total pod production through plants m^{-2} ($r_{13}P_{15}$ = –0.66 to –0.81), but the strong direct effect of pods plant^{-1} overshadowed the negative indirect effect.

These results indicate that desi chickpea seed yield potential can be increased by increasing plant population density to produce a sufficient amount of pods per unit area, whereas the kabuli chickpea seed yield potential can be increased by promoting pod production via increasing both the number of pods per plant and plants per unit area. In a previous study, Gan et al. (2003) reported that desi chickpea increased fertile pods m^{-2} by 28% as plant population density increased from 20 to 50 plants m^{-2}, whereas this level of PPD changes increased pods m^{-2} by 10% for a large-seeded kabuli crop. On average, kabuli plants produced 45 to 50% as many pods m^{-2} as desi plants under normal growing conditions. It seems that kabuli chickpea has a low capacity of pod production, particularly when the crop is grown in an environment where growth resources are limited. Our study clearly indicates that total number of pods per unit area is the greatest contributor to the seed yield for both market classes of chickpea grown in the semiarid environment. These results are in agreement with those found elsewhere in annual pulses, including kabuli chickpea (Beech and Leach 1989), desi chickpea (Jettner et al. 1999), faba bean (Marcellos and Constable 1986), soybean(Ballet al. 2001), and lentil (*Lens culinaris* Medik.) (Siddique et al. 1998).

Seed Weight

Seed weight is an important contributor to chickpea seed yield. Seed weight was negatively correlated with the length of vegetative growth in both desi (Tables 4) and kabuli (Table 5) chickpea regardless of the growing environments (i.e., CS or NT). Path coefficient analyses provided more insights to the relationship between seed weight and other yield components (Table 8). Desi chickpea seed weight was positively affected by the period of reproductive growth and seeds pod^{-1} only when the crop was grown on CS. When desi was grown on NT, none of the yield components affected the seed weight. The average seed weight of the desi crop is relatively stable across different growing environments (data not shown), though better soil moisture conditions under fallow lengthened the period from flowering to maturity, allowing extra time for seed fill.

Similar to desi, the seed weight of kabuli chickpea was highly related to the length of the reproductive period and seeds pod^{-1} only when the crop was grown on CS (Table 8). However, the magnitude of this effect was smaller than that measured for the desi crop. When the kabuli crop was grown on NT, none of the yield-related variables directly influenced seed weight although the seed weight was positively correlated with seeds pod^{-1}.

These observations indicate that mean seed weight of both desi and kabuli chickpea can be increased, at least to some extent, by promoting early flowering and shortening the vegetative growth period. Promoting earlier seed set may increase both the number of seeds per pod and the weight of individual seeds. The potential to increase seed weight for kabuli chickpea may be at the expense of reducing the number of pods per plant, but this may impact the seed size distribution in the harvested seedlot. In a previous study, Gan et al. (2003) demonstrated that plant population did not affect mean seed weight in kabuli chickpea, but the plants at a lower plant density produced a greater proportion of large-sized (>9-mm-diameter) seed in the harvested seedlot. The kabuli crop grown on CS produced >70% of seeds that were >9-mm in diameter; this proportion of the large-sized seed was significantly higher than when the kabuli was grown on NT.

In summary, this study determined the detailed interrelationships among yield-related variables of chickpea using both correlation coefficient and path analyses, and also identified the key yield components for enhancing chickpea seed yield potential. The results of this study indicate that the number of pods per unit area is the most important component contributing to seed yield in both desi and kabuli chickpea. The strong association between pods per unit area and seed yield exists regardless of the growing conditions. Among the two market classes of chickpea, kabuli chickpea produces about 50% of the pods produced by the desi, and the differences in pod production between the two market classes become more pronounced as the pulses are grown on NT compared to those grown on CS. The kabuli class had a weaker capacity for compensation among yield components than the desi class, particularly when grown in an environment where plant-to-plant competition for resources was high. When resources were limited for plant growth, kabuli plants produced a high percent of infertile pods, whereas desi chickpea produced a consistently low ratio between infertile and fertile. Unlike cereal crops where the kernel weight of a given cultivar is usually stable across different growing conditions, the seed weight of chickpea crop serves as a strong, flexible contributor to seed yield. These results clearly indicate that the seed yield potential of desi chickpea can be increased by increasing plant population density, whereas the yield potential of kabuli chickpea can be increased by prolonging the reproductive growth period, promoting pod production and fertility, and increasing mean seed weight. These goals of increasing chickpea seed yield in a semiarid environment can be achieved through genetic improvement and the use of optimal agronomic management practices.

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