Archives of Agronomy and Soil Science
Vol. 57, No. 8, December 2011, 853–871

Corn yield response to crowding stress and cropping season

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(*Received 11 January 2010; final version received 8 June 2010*)

Corn (*Zea mays* L.) is planted in two seasons per year in northern Iran (mid-April as a main crop and mid-June as a second crop). The main objective of this study was to determine whether corn yield response would differ between these two seasons and different plant populations. Two field experiments were conducted at the Agricultural Research Center of Golestan – Iran in 2007 and 2008 at different planting densities. The results showed that the values of grain yield and most traits were significantly lower in the second season. Maximum grain yield was observed at planting densities of 6.5 plants m^{-2} in the first season, whereas in the second season grain yield was the same for planting densities between 2.5 and 12.5 plants m^{-2}. Based on the second-year experimental results, the following functions were fitted to show the relationship between yield ha^{-1} (Y) and planting densities (X) for the first and second seasons, respectively: ($Y = -167.6X^2 + 2672.2X + 511.77$; $R^2 = 0.992$) and ($Y = 1200.1 \ln(X) + 2924.4$; $R^2 = 0.935$). This study found that the optimum plant population was 6.5 plants m^{-2} under low heat stress, and should be reduced to 2.5–4.5 plants m^{-2} under heat stress conditions.

Keywords: maize; crowding stress; cropping season; yield and yield components

Introduction

Golestan Province is located in northern Iran near the Caspian Sea. It has a Mediterranean climate: cool in spring and warm in the summer. The average daily mean temperatures in spring and summer are 20.8 and 27.8°C, respectively. During the last decade, August has experienced the highest daily mean maximum temperature (T_{max}) (34.6°C), the highest daily mean evaporation (7.1 mm) and the least precipitation (13.14 mm). Corn (*Zea mays* L.) is usually planted in two seasons per year: mid-April as a main crop and mid-June as a second crop after the wheat harvest. According to previous studies, maximum grain yields (9–11 t ha^{-1}) were obtained at densities between 5.5 and 6.5 plants m^{-2} in the first and second seasons (Chogan 1993; Mokhtarpour 1997). But during the last decade, the weather has

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ISSN 0365-0340 print/ISSN 1476-3567 online

http://dx.doi.org/10.1080/03650340.2010.499901
http://www.tandfonline.com

become warmer in the summer and the yield has reduced for the second planting date, so that in 1999 and 2000 the grain yield was reduced to 4.7 t ha^{-1} (Mokhtarpour and Mosavat 2001). A preliminary evaluation showed that the percentage of barren stalks inside the canopy increased dramatically for summer planting dates, but ears were observed in most plants in border lines (unpublished data of corresponding author). Based on this observation and the results of other studies (Norwood and Currie 1996; Larson and Clegg 1999), it seems that planting density should be decreased under stress conditions. Crowding stress or planting density is a major factor in determining the degree of competition between plants. Yield per plant decreases as crowding stress increases. Yield reduction is mostly due to lower ear numbers (barrenness) (Hashemi et al. 2005), fewer kernels per ear (Capristo et al. 2007), lower kernel weight (Monneveux et al. 2005) or a combination of these components. Grain yield per unit area is the product of grain yield per plant and planting density. The optimum plant population is influenced by planting date (Norwood 2001), hybrid/variety (Edwards et al. 2005; Sarlangue et al. 2007), soil fertility (Polito 1987) and water limitation (Norwood and Currie 1996; Nielsen et al 2002). Sarlangue et al. (2007) showed that increases in grain yield at higher plant densities were associated with increases in biomass production, and a greater harvest index (HI) with increasing planting density was observed only in the hybrids with the least plasticity. Polito (1987) reported that high planting density did not increase grain yield but did increase the percentage of barren stalks. Tollenaar (1989) found that increasing the planting density increased total dry matter production and decreased HI. Tollenaar et al. (2006) reported that crowding stress affected dry matter accumulation but did not affect HI. Norwood and Currie (1996) and Larson and Clegg (1999) found that under stress conditions, plant populations should be reduced.

Many researchers have reported the effect of high temperature on the growth and yield of corn. Using long-term weather data, Thompson (1986) concluded that higher mean seasonal temperature was correlated with lower grain yield. Lorgeou (1990), cited by Khabba et al. (2001), reported that daily growth rate per kernel correlated with mean daily temperature, the optimum growth rate being observed at a mean temperature of 21°C. CA Jones and Kiniry (1986) reported that temperatures >34°C damage photosynthesis apparatus and reduce dry matter accumulation. In the CERES-Maize model component in the Decision Support System for Agrotechnology Transfer (DSSAT ver. (4.5)), grain growth rate is related to temperature via a quadratic function of mean daily temperature and the potential growth rate related to 25°C. Frey (1981) reported that stress before silking may cause ears to fail to develop, whereas stress after pollination results in reduced kernel numbers or kernel abortion. Several studies have showed that kernel number is most susceptible to stress during the period between two weeks before and two to three weeks after silking (Tollenaar and Daynard 1978; Kiniry and Ritchie 1985; Fischer and Palmer 1984; Cirilo and Andrade 1994). Inhibition of photosynthesis has been observed after short exposure (15–60 min) to moderately high temperature (35–40°C) in maize (Crafts-Brandner and Salvucci 2002). In a growth chamber study, Badu-Apraku et al. (1983) observed a 42% loss in grain weight per plant when the day/night temperature from 18 days post-silking to maturity was increased from 25/15 to 35/15°C. For maize grown at 20 and 30°C in a controlled environment, Hunter et al. (1977) observed a higher grain yield at lower temperatures because of an increase in the length of the grain-filling period.

Contrary to other reports for maize grown in controlled environments, Muchow (1990) showed under field conditions that grain yield was unaffected by temperature, when temperature ranged from 25.4 to 31.6°C during the period from pollination to 80% maximum grain size.

Therefore, the main objectives of this study were to determine whether corn growth and yield would differ between the two seasons (in particular, because the temperature between the two seasons would be different), as well as different planting densities.

Materials and methods

Two field experiments were conducted as a randomized complete block design on 19 April (as a main crop) and 18 June (as a second crop) in 2007 and 2008 in the Agricultural Research Center of Golestan – Iran (36°53′N, 54°21′E). A late-maturing hybrid (Sc 704) was planted in all experiments. In 2007, each experiment included three planting densities (0.16, 4.5 and 6.5 plants m^{-2}) with four replications, and in 2008, each experiment included seven planting densities (0.16, 2.5, 4.5, 6.5, 8.5, 10.5 and 12.5 plants m^{-2}) with four replications. The purpose of including a low planting density (0.16 plants m^{-2}) was to obtain the potential growth and yield of maize without competition by other maize plants. To reach this planting density, eight plants were planted next to the main experiment at a distance of 2.5 m from each other in a quadrate shape at both planting dates in both years. Four of eight plants were cut at the tasseling stage to calculate the leaf area and the rest were harvested at physiological maturity to calculate yield and yield components.

In the main experiments, each plot contained four rows, each 7 m in length. The distance between rows was 75 cm and the planting densities were changed with changing distance between plants per row. Plants row^{-1} distances were 53.5, 30, 20, 15.7, 12.7 and 10.7 cm for planting densities 2.5, 4.5, 6.5, 8.5, 10.5 and 12.5 plants ha^{-1}, respectively. Four more planting densities were added in the second year to justify the following two possible assumptions that may be stated by readers based on the first year's experimental results. In 2007, a plant population of 6.5 plants m^{-2} produced the maximum grain yield in the first season and in the second season planting densities of 4.5 and 6.5 plants m^{-2} produced the same grain yield.

(1) Yield may increase in the first season if we included planting densities >6.5 plants m^{-2}.
(2) Because planting densities of 4.5 and 6.5 plants m^{-2} showed the same grain yield in the second season, lower planting densities may still produce the same yield.

The seed bed was prepared a few days before sowing. The experiments were planted manually. Three seeds were planted in each hole and then thinned to one plant per hole at the two-leaf stage, so that the surviving plants met the intended planting densities. All experiments were conducted without any limitations in water or nutrients. Soil water was kept at $>$ 50% field capacity during the growing season by furrow irrigation. Soil samples were used to determine water content by a standard gravimetric method (Cuenca 1989). Two soil samples were taken from blocks one and three at 0–15, 15–30 and 30–45 cm soil depth profile in every three days. Irrigation water was applied by considering the water available in the root zone.

Fertilizers were applied based on soil test results. Soil properties were determined prior to planting (Table 1). A broadcast application of 60–45–100 kg ha^{-1} (N-P-K) was incorporated into the seed bed. The sources of N, P and K were urea, triple super phosphate with 46% P_2O_5, and potassium sulfate with 50% K_2O, respectively. An additional 100 kg N ha^{-1} was applied as a side dressing at the five- and nine-leaf stages (50 kg ha^{-1} in each stage). Weeds and insects were adequately controlled during the growing seasons. To control weeds, a mixture of two herbicides, Atrazine [2-chloro-4-(ethylamine) -6-(isopropylamine)-s-triazine] and Lasso [2-chloro-2′-6′-diethyl-N-methoxymethyl)-acetanilide], was used immediately after planting at rates of 1 kg ha^{-1} and 3.5 l ha^{-1}, respectively. Weed control was also carried out manually when necessary.

In the first season, insects did not cause serious damage in the fields so no insecticide was used for this season in either year. In the second season, to prevent damage by the European corn borer (*Ostrinia nubilalis*), a mixture of two pesticides, Larvin® (Thiodicarb) and Nuvacron® (Monocrotophos), at rates of 1 kg ha^{-1} and 1.5 l ha^{-1}, respectively was used.

To evaluate the effect of season or crowding stress on a specific growth stage, all phenological events including planting date, emergence date, tasseling, silking, milk stage, dough stage, physiological maturity and harvesting time were recorded during the growing season based on their appearance in 50% of the plants in each plot. From weather data, cumulative mean daily temperature, cumulative solar radiation and cumulative growth degree day (GDD) were computed to reach to different growth stages in all treatments. Growth degree day was calculated using the following formula:

$$GDD = (T_{\min} + T_{\max})/2 - T_{\text{base}} \tag{1}$$

where $T_{\max}$ and $T_{\min}$ are maximum and minimum daily air temperatures, respectively, and the base temperature at which development ceased T_{base} was 8°C. According to Tsuji et al. (1998), when mean daily temperature (T_{mean}) exceeded 30°C, T_{mean} was assumed to be 30°C.

To measure the leaf area index (LAI), four plants were cut from the end of two central rows considering the border effect in the flowering stage. Leaf area was measured using the 'Area Measurement System' (Delta-T Devices Ltd, Cambridge, UK). To calculate plant height, stem diameter, ear length, number of rows per ear and number of seeds per row, 10 plants from each of the two central rows from each plot were randomly harvested individually at physiological maturity and the mean

Table 1. Soil properties, determined prior to planting in two years.

Soil Parameters	2007	2008
Depth (cm)	0–30	0–30
Soil texture	Silty clay loam	Silty clay loam
pH of paste	7.2	7.3
Electrical conductivity (dS m^{-1})	1.35	1.29
Organic carbon (%)	1.5	1.5
Available phosphorus (mg kg^{-1})	8.6	8.9
Available potassium (mg kg^{-1})	333	327

values recorded. Stem diameter was measured on the first internode above ground level. Plant and ear numbers in all plots were counted to calculate the number of ears per plant. To calculate total dry matter (TDM), yield (grain weight), harvest index (HI) and weight per thousand seeds (W1000), 5 m of the two central rows, considering the border effect, were harvested in each plot. After separating the different parts of the plants, including (stem + leaf + tassel), cob, husk and grain, the fresh weights were measured and a sample of each part was dried to a constant weight at 75°C for approximately three days. Dry weights were recorded based on 14% humidity in each part. To analyze the data, based on Gomez and Gomez (1984), a combined analysis over seasons ANOVA was carried out in each year using SAS software (Ver. 9.1, SAS Institute, Cary, NC, USA). The least significant differences test (LSD) was used to compare the mean values in each trait. Using Microsoft Excel 2007, the data for the second-year experiments were used to fit the best functions, to show the relationship between planting density and different traits including grain weight plant^{-1}, grain weight m^{-2}, TDM plant^{-1}, TDM m^{-2}, LAI and HI.

To evaluate the accuracy of the developed equations, data from the first-year experiments were used. Model validity was tested using two goodness-of-fit indicators, the root mean square error (RMSE) and the index of agreement (*d*) (Willmott et al. 1985). Their formulae are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{N}}$$

Where y_i, $\hat{y}_i$ are the observed and predicted y values, respectively, and $\bar{y}$ is the mean of the entire N observed y values. Low values of RMSE illustrate high accuracy whereas high d indicates high accuracy.

$$d = 1 - \frac{\sum_{i=1}^{N}|y_i - \hat{y}_i|}{\sum_{i=1}^{N}(|\hat{y}_i - \bar{y}| + |y_i - \bar{y}|)}$$

Results and Discussion

Effect of season

The results showed that season had a significant effect on most traits ($p \leq 0.01$) in both years (Tables 2 and 3). Values for LAI, stem diameter, ear per plant, W1000, TDM, harvest index (HI) and grain weight decreased in the second season in 2007 (Table 4). Almost the same trend was observed in 2008 (Table 4). Because all experiments were conducted with no water and nutrient or pest or disease stress, the only main difference between the two seasons was the temperature (Table 5). To evaluate the effect of temperature on yield and yield components, the following four indices were computed in both seasons: length of plant growing period, mean daily temperature, GDD and days with maximum temperature (T_{max}) $\geq$ 34°C (Table 5).

The recorded phenological data showed that days to emergence, days to anthesis and days to maturity decreased in the second season in both years (Table 5), therefore a shortening of the plant growing period due to higher temperature is one of the reasons for the reduced yield and yield components in the second season. Mean daily temperature (MDT), one of the main factors that influenced maize

Table 2. Analysis variance of traits in 2007.

S.O.V	df	MS										
		Plant height	Stem diameter	LAI	Ear $plant^{-1}$	Ear length	Seed row^{-1}	Rows number	W1000	TDM	Grain weight	HI
Season	1	0.255^{ns}	6.06**	3.84**	1.235**	1.696^{ns}	1.706^{ns}	0.166^{ns}	5651.3**	8.131*	45.36**	1651.7**
Block(Season)	6	86.492^{ns}	1.371^{ns}	0.032^{ns}	0.011^{ns}	0.565^{ns}	15.047^{ns}	0.611^{ns}	249.6^{ns}	1.606^{ns}	0.286^{ns}	3.001^{ns}
Planting density	2	6898.8**	596.46**	39**	0.943**	77.031**	102.78**	0.666^{ns}	6382.1**	946.6**	175.8**	41.564**
Season density	2	133.85^{ns}	8.177^{ns}	1.19^{ns}	0.448**	32.69**	126.18**	2.666^{ns}	984.65^{ns}	1.105^{ns}	9.37**	4.096^{ns}
Error	12	51.402	2.329	0.023	0.0054	1.4	5.126	0.777	324.22	1.395	0.282	4.16
Total	23											
CV, %		3.01	6.05	5.98	6.69	5.92	4.96	6.33	6.7	8.74	8.99	4.65

Note: ns, not significant; *, significat at a 5% probability level; **, significant at a 1% probability level.
LAI, leaf area index; W1000, 1000 seed weight; TDM, total dry matter; HI, harvest index.

Table 3. Analysis variance of traits in 2008.

		MS										
S.O.V	df	Plant height	Stem diameter	Ear plant^{-1}	Ear length	Seed row^{-1}	Rows number	LAI	W1000	TDM	Grain weight	HI
Season	1	498.01^{ns}	131.45**	1.7980**	21.43**	436.52**	0.36^{ns}	4.78*	10858.2**	328.59**	170.52**	1438.1**
Block (Season)	6	87.99^{ns}	3.99^{ns}	0.0006^{ns}	0.51^{ns}	10.49^{ns}	0.21^{ns}	0.60^{ns}	1345.87^{ns}	3.17^{ns}	0.615^{ns}	9.79^{ns}
Planting density	6	2715.5**	154.48**	0.5872**	105.78**	561.89**	2.65**	36.67**	1370.85^{ns}	362.70**	58.31**	80.19**
Season × density	6	45.81^{ns}	14.29*	0.1612**	4.28**	80.19**	2.32**	0.53^{ns}	2429.87^{ns}	58.76**	8.95**	122.06**
Error	36	73.95	5.07	0.0018	1.09	6.02	0.12	0.58	1051.19	3.27	0.52	4.82
Total	55											
CV, %		3.48	9.09	4.69	5.71	6.24	2.4	20.55	9.61	11.91	11.39	5.32

Note: ns, not significant; *, significat at a 5% probability level; **, significant at a 1% probability level.
LAI, leaf area index; W1000, 1000 seed weight; TDM, total dry matter; HI, harvest index.

Table 4. The effect of season on some traits in 2007 and 2008.

Traits	2007		2008	
	Season 1	Season 2	Season 1	Season 2
Ears per plant	1.33 a	0.87 b	1.09 a	0.73 b
W1000 (g)	284.0 a	253.3 b	286.04 a	258.19 b
Grain weight (kg ha^{-1})	7286 a	4536 b	8099 a	4609 b
HI (%)	52.14 a	35.55 b	46.13 a	36.22 b
TDM (kg ha^{-1})	14090 a	12930 b	17970 a	13130 b
LAI	2.98 a	2,16 b	4.01 a	3.42 b
Stem diameter (mm)	26.8 a	23.5 b	26.30 a	23.24 b
Ear length (cm)	19.6 a	20.2 a	18.90 a	17.66 b
Seed per rows	45.9 a	45.5 a	42.07 a	36.48 b

Note: Means with same letter in each row are not significantly different at a 5% probability level in each year.
LAI, leaf area index; W1000, 1000 seed weight; TDM, total dry matter; HI, harvest index.

growth and yield, increased in the second season (~28 vs. ~24°C), although MDT during the grain-filling period was almost the same in both seasons. Using long-term weather data, Thompson (1986) observed the same trend and concluded that maize grain yield decreased with increasing seasonal mean temperature.

The number of days with $T_{max} \geq 34$°C was used as another index to explain how high temperature affected yield and yield components. In the second season, the number of days with $T_{max} \geq 34$°C increased dramatically in both years. In 2007, in the first season, 25 days (23.14% of the total plant growing period) experienced $T_{max} \geq 34$°C, mostly during the last days of the plant growing period. However, in the second season, 45 days experienced $T_{max} \geq 34$°C (46.87% of the total plant growing period), spread over all stages of plant growth. The same trend was observed in 2008. In the first season, 17 days (15.88% of the total plant growing period) experienced $T_{max} \geq 34$°C, mostly during the last days of the plant growth period, whereas in the second season 38 days (38% of the total plant growing period) experienced $T_{max} \geq 34$°C, which occurred throughout the plant growing period (Table 5).

High temperatures caused stalk barrenness, and the number of ears per plant decreased in the second season (Table 4). High temperatures also reduced the number of seeds per ear in 2008 (Table 4). The result of this study is consistent with Frey (1981) who reported that stress before silking may increase the barrenness of stalks and stress after silking results in limited kernel numbers or kernel abortion.

HI decreased in the second season because the rate of reduction in grain yield was higher than the rate of reduction in TDM. This means that reproductive organs are more susceptible to high temperature stress than vegetative organs.

Based on the results of this study, higher mean daily temperature and more days with $T_{max} \geq 34$°C during the plant growing period were the main reasons for the reduction in number of ears per plant, number of kernels per ear, LAI, W1000, HI, TDM and grain yield in the second season. The results of this study are in line with the reports of many other researchers who concluded that high temperature damages the yield and yield components in maize (Badu-Apraku et al. 1983; Fischer and Palmer 1984; Kiniry and Ritchie 1985; CA Jones and Kiniry 1986; Thompson 1986; Cirilo and Andrade 1994, 1996; Khabba et al. 2001).

Table 5. Number of days (No. D), Mean daily temp (MDT), Σ Mean daily temp (ΣMDT), Day with $T_{max} > 34°C$ ($DT_{max} > 34°C$), ΣGrowth degree day (ΣGDD) and ΣSolar radiation (ΣSRAD) that maize need to reach different phenological stages in two seasons in 2007 and 2008.

	No. D		MDT		Σ MDT		ΣGDD		ΣSRAD		$DT_{max} >$ 34°C	
Days to phenological stages in 2007	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Days to emergence	11	5	15.08	28.1	165.9	140.5	77.9	98.7	129.9	98.9	0	1
Days to anthesis	68	54	21.9	27.7	1490.3	1497	946.3	1065	1087	1014	13	19
Anthesis to maturity	40	42	27.4	28.6	1099.1	1202	779.1	866	682.7	809	12	25
Days to maturity	108	96	23.9	28.1	2589	2702	1725.5	1925	1769.8	1816	25	45
Days to phenological stages in 2008												
Days to emergence	8	5	19.4	25.6	155.1	128	75.1	78	144.3	91.6	2	0
Days to anthesis	65	60	22.1	27.9	1437.9	1676	917.9	1195	1181.6	1028	4	16
Anthesis to maturity	42	40	28	28.6	1175.5	1143	835.2	819.1	743.9	740.1	13	22
Days to maturity	107	100	24.4	28.2	2613.4	2818	1745.4	2004	1925.6	1769	17	38

Note: S1, season 1, S2, Season 2.

Calculation of GDD for different plant growth stages in both seasons and both years indicated that cumulative GDD (ΣGDD) increased in the second season (Table 5). This result showed that the ΣGDD reached for a specific stage of growth may change for a given hybrid under different conditions. The result of this study is in agreement with other researchers. Stevens et al. (1986) reported an interaction effect between genotype and planting date for GDD accumulation. The thermal interval between planting and physiological maturity of one popcorn hybrid decreased because planting was delayed, whereas that of a second hybrid remained the same and that of a third increased. In another study, Roth and Yocum (1997) reported that delayed planting increased cumulative GDD to physiological maturity for three hybrids in a drought year, but decreased ΣGDD to physiological maturity for the same three hybrids in the following year under less-stressful conditions. Nielsen et al. (2002) reported that ΣGDD decreased for a given hybrid with delay in planting date.

Planting density

Planting density affected yield and yield components in both years. Planting density had a significant effect on LAI ($p \leq 0.01$) in both years (Tables 2 and 3). In 2007, the highest value of LAI (4.4) was obtained at a planting density of 6.5 plants m^{-2} (Table 6). In 2008, the highest value of LAI (5.47–5.75) was obtained at planting densities between 8.5 and 12.5 plants m^{-2} (Table 6). Using the second-year experimental data, two quadratic equations with high R^2 were fitted to show the relationship between planting density and LAI in both seasons (Table 7 and Figure 1). The developed equations were tested against the first-year experimental data using two goodness-of-fit indicators, RMSE and *d*. The low values of RMSE and the high values of *d* showed that the developed equations can predict LAI with high accuracy in different planting densities (Table 7).

Planting density had significant effect on plant height ($p \leq 0.01$). The lowest plant height was observed at a low planting density (0.16 plants m^{-2}) in both years ($\sim$200 cm), because there was no competition between plants in this treatment. The same plant height was observed at planting densities of 4.5 and 6.5 plants m^{-2} in 2007, whereas the greatest plant height (2.58–2.64 m) was obtained at planting densities of 10.5 and 12.5 plants m^{-2} in 2008 (Table 6).

Planting density had significant effect on kernel weight (W1000) in the first year ($p \leq 0.01$). High kernel weight had been observed in single plants and the same kernel weight was observed at planting densities of 4.5 and 6.5 plants m^{-2} (Tables 2 and 6). However, in 2008, planting density did not have a significant effect on W1000 ($p < 0.05$). Because W1000 showed the same response to different planting densities, grain yield was defined using other yield components such as ears per plant and kernels per ear. The result of this study is consistent Hashemi et al. (2005) who reported that the reduction in grain yield at a high planting density was not attributed to W1000 but to a reduction in the number of kernels per row.

Because of intraspecific competition, seeds per ear, ear length and stem diameter decreased with increasing planting density in both years (Table 6).

Interaction effect

The interaction between planting density and season had a significant effect on grain yield, ears per plant, seeds per row and ear length ($p \leq 0.01$) in 2007 (Tables 2

Table 6. The effect of planting density on some traits in 2007 and 2008.

	Planting density (plants m^{-2}) in 2007			Planting density (plants m^{-2}) in 2008						
Traits	0.16	4.5	6.5	0.16	2.5	4.5	6.5	8.5	10.5	12.5
Plant height (cm)	204.6 b	254.6 a	256.2 a	2.07 d	2.48 c	2.48 c	2.49 c	2.53 bc	2.58 ab	2.64 a
Stem diameter (mm)	35.13 a	20.81 b	19.62 b	32.43 a	27.98 b	25.82 bc	23.93 dc	22.68 de	20.56 ef	19.98 f
Ear length (cm)	23.4 a	19.11 b	17.36 c	22.93 a	22.15 a	20.01 b	17.92 c	17.12 c	14.31 d	13.53 d
Grain weight (kg ha^{-1})	533 c	8065 b	9135 a	543 e	5789 d	7095 bc	8207 a	8217 a	7723 ab	6901 c
TDM (kg ha^{-1})	1110 c	17940 b	21470 a	1040 d	13760 c	17640 b	19520 a	20190 a	19040 ab	17660 b
HI (%)	45.99 a	44.09 a	41.45 b	47.96 a	41.65 b	39.04 c	40.37 bc	39.30 c	39.76 bc	39.35 c
Ear per plant	1.5 a	0.89 b	0.91 b	1.5 a	0.875 b	0.878 b	0.895 b	0.858 b	0.785 c	0.641 d
W1000 (g)	300.2 a	259.9 b	245.8 b	283.5 ab	294.4 a	274.7 ab	267.6 ab	263 ab	256.9 ab	264.4 ab
Seed row^{-1}	49.31 a	45.18 b	42.17 c	50.5 a	48.65 a	42.13 b	38.63 c	35.6 d	30.9 e	28.53 e
LAI	0.129 c	3.23 b	4.40 a	0.13 e	1.88 d	3.02 c	4.23 b	5.47 a	5.52 a	5.75 a
Rows number	14.25 a	13.75 a	13.75 a	15.00 b	15.42 a	15.01 b	14.75 bc	14.40 c	14.00 d	13.85 d

Note: Means with same letter in each row are not significantly different at a 5% probability level in each year.
LAI, leaf area index; W1000, 1000 seed weight; TDM, total dry matter; HI, harvest index.

Table 7. The developed equations for estimating maize grain yield, TDM, LAI and HI in the first and second seasons using second-year experimental data. Root mean square error (RMSE) and the index of agreement (*d*) were used to show the validity of the developed equations using the first-year experimental data.

Traits	Season 1	R^2	RMSE	*d*	Season 2	R^2	RMSE	*d*
TDM (kg ha^{-1})	$Y = -429.88X^2 + 6493.2X + 1111.8$	0.976	2416.9	0.88	$Y = 3942.2 \ln(X) + 7793.54$	0.966	3735.5	0.76
Grain weight (kg ha^{-1})	$Y = -167.6X^2 + 2672.2X + 511.77$	0.992	405.8	0.95	$Y = 1200.1 \ln(X) + 2924.4$	0.935	1315.4	0.72
LAI	$Y = -0.0336X^2 + 0.9468X - 0.1421$	0.993	0.36	0.91	$Y = -0.0305X^2 + 0.8134X - 0.0501$	0.997	0.21	0.93
HI %	$Y = 0.2693X^2 - 3.4687X + 52.8333$	0.662	7.2	0.22	$Y = -1.0915X + 43.267$	0.903	3.99	0.35

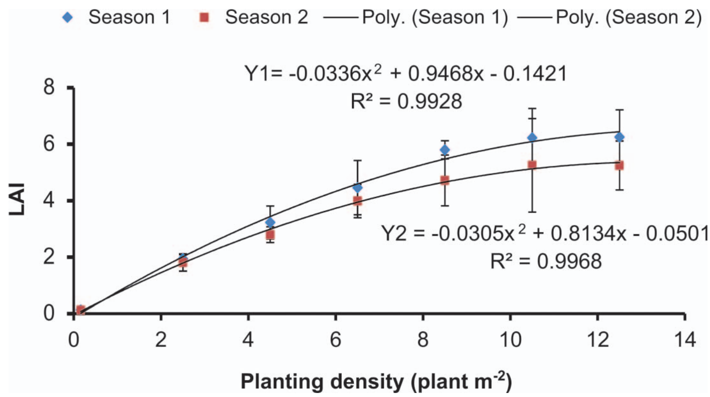

Figure 1. Relationship between planting density and leaf area index (LAI) in two seasons.

Table 8. The interaction effect between season and planting density on some traits in 2007.

	Planting density (plants m^{-2})					
	Season 1			Season 2		
Traits	0.16	4.5	6.5	0.16	4.5	6.5
Ear length (cm)	20.80 a	20.01 b	18.27 b	26 a	18.21 b	16.46 b
Seeds per rows	45 b	47.52 a	44.94 b	53.62 a	42.84 b	39.4 c
Ears per plant	2.00 a	1.00 b	0.99 b	1.00 a	0.83 ab	0.79 b
Grain weight (kg ha^{-1})	705 c	9745 b	11408 a	361 b	6386 a	6863 a

Note: In each season, means with same letter in each row are not significantly different at the 5% probability level.

and 8), whereas the interaction between planting density and season had a significant effect on eight of eleven traits in 2008 ($p \leq 0.01$) (Tables 3 and 9). In 2008, in the first season, the maximum values of TDM (24,600–25,960 kg ha^{-1}) were observed for the middle densities (6.5 and 8.5 plants m^{-2}), whereas in the second season, the maximum values of TDM (18,430–18,920 kg ha^{-1}) were observed at high planting densities (10.5 and 12.5 plants m^{-2}) (Table 9). Using the second-year experimental data, the best equations were fitted to show the relationship between planting density and TDM ha^{-1} for the two seasons. In the first season, a quadratic trend was observed, whereas in the second season a logarithmic trend was observed (Table 7 and Figure 2). The developed equations were tested against the first-year experimental data. The result showed that the developed equation could predict TDM with a high degree of accuracy in the first season (low value of RMSE: 2416 kg ha^{-1} and high value of *d*: 0.88). However, the developed equation for predicting TDM in the second season could not estimate TDM with a high degree of accuracy (RMSE: 3735 kg ha^{-1} and *d*: 0.76) (Table 7).

The interaction between planting density and season had a significant effect on the number of ears per plant ($p \leq 0.01$) in both years (Tables 8 and 9). In the season of 2007 and 2008, plants at a low planting density (0.16 plants m^{-2}) produced two ears per plant (Table 8) in both years, whereas one ear per plant was produced at

Table 9. The interaction effect between season and planting density on some traits in 2008.

	Planting density (plants m^{-2})													
	Season 1							Season 2						
Traits	0.16	2.5	4.5	6.5	8.5	10.5	12.5	0.16	2.5	4.5	6.5	8.5	10.5	12.5
Stem diameter (mm)	36.7 a	29.2 b	27.9 bc	25.2 dc	23.4 de	20.9 e	20.7 e	28.1 a	26.7 ab	23.7 bc	22.6 dc	21.9 dc	20.4 dc	19.0 d
Ear length (cm)	22.8 ab	23.2 a	21.9 b	18.7 c	17.5 d	14.2 e	13.7 e	23.0 a	21.0 b	18.0 c	17.1 c	16.7 c	14.4 d	13.2 d
Seeds per rows	47.2 bc	52.3 a	48.6 b	43.7 c	39.3 d	32.2 e	30.9 e	53.7 a	44.9 b	35.5 c	33.4 dc	31.8 de	29.6 ef	26.1 f
Rows number	14.0 c	15.2 a	15.4 a	15.3 a	14.7 b	14.1 c	14.2 c	16.0 a	16.0 a	14.6 b	14.1 bc	14.1 dc	13.9 d	13.5 d
Ears per plant	2.00 a	1.00 b	1.0 b	1.0 b	1.0 b	0.92 c	0.76 d	1.0 a	0.75 b	0.75 b	0.79 b	0.71 bc	0.64 c	0.51 d
Grain (kg ha^{-1})	716 e	6515 d	9340 b	11082 a	11163 a	9669 b	8206 c	370 b	5063 a	4850 a	5332 a	5271 a	5776 a	5597 a
TDM (kg ha^{-1})	1230 e	15800 d	22070 bc	24600 ab	25960 a	19640 c	16400 d	800 d	11670 c	13200 bc	14440 b	14420 b	18430 a	18920 a
Harvest index (%)	55.3 a	40.5 d	41.8 cd	44.4 c	42.6 cd	48.6 b	49.4 b	42.1 a	42.7 a	36.2 b	36.2 b	35.90 b	30.9 c	29.2 c

Note: In each season, means with same letter in each row are not significantly different at the 5% probability level.

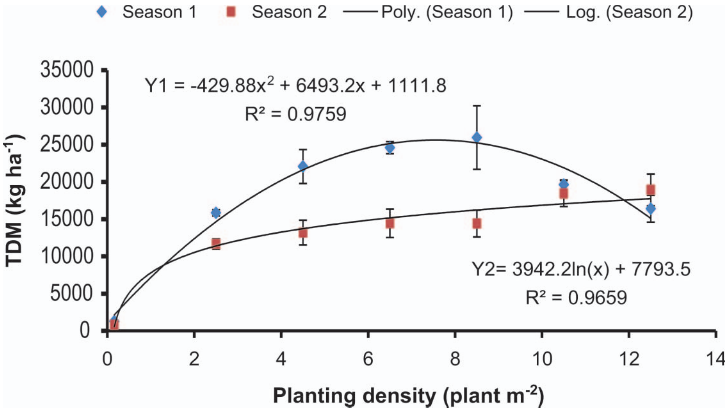

Figure 2. Relationship between planting density and total dry matter (TDM) ha^{-1} in two seasons.

planting densities between 2.5 and 8.5 plants m^{-2} in 2008 (Table 9). The same trend was not observed in the second season; plants at a low planting density (0.16 plants m^{-2}) had one ear per plant, and the number of ears per plant decreased with increasing planting density (Table 9). Almost the same trend was observed in 2007 (Table 8). Polito (1987), Hashemi et al. (2005) and Sarlangue et al. (2007) found the same trend and reported that the number of barren stalks increased with increasing planting density.

Planting density and the interaction between planting density and season did not have a significant effect on the number of rows per ear in 2007 (Tables 6 and 8). The same trend was not observed in 2008; in the first season of 2008, the maximum number of rows per ear (15.3–15.4) was obtained for the middle planting densities (6.5 and 8.5 plants m^{-2}), whereas in the second season, the maximum value (16) was obtained at the first two planting densities (0.16 and 2.5 plants m^{-2}). Higher temperatures in the second season increased the seed abortion rate and caused a reduction in the number of rows per ear at high planting densities (Table 8).

Number of seeds per row was affected by an interaction effect between planting density and season in both years (Tables 2 and 3). In the first season of 2007, the maximum number of seeds per row (47.52) was observed at a planting density of 4.5 plants m^{-2}, whereas in the second season, the maximum value (53.62) was observed for single plants (0.16 plants m^{-2}) (Table 8). In the first season of 2008, the maximum number of seeds per row (52.32) was observed at the second planting density (2.5 plants m^{-2}), whereas in the second season, the maximum value (53.75) was observed for single plants (0.16 plants m^{-2}). The main reason for this was that the single plants in the first season produced two ears per plant in both years, whereas in the second season they produced one ear per plant (Table 9).

The interaction between planting density and season did not have significant effect on HI in 2007 ($p < 0.05$) (Table 2) and a higher HI value was observed at lower planting densities in 2007 (0.16 and 4.5 plants m^{-2}) (Tables 2 and 6). In 2008, the interaction between planting density and season had a significant effect on HI ($p \leq 0.01$). In the first season of 2008, the maximum value of HI (55.32%) was observed at the lowest planting density (0.16 plants m^{-2}) and the minimum value (40–42%) was observed at planting densities between 2.5 and 8.5 plants m^{-2}, whereas

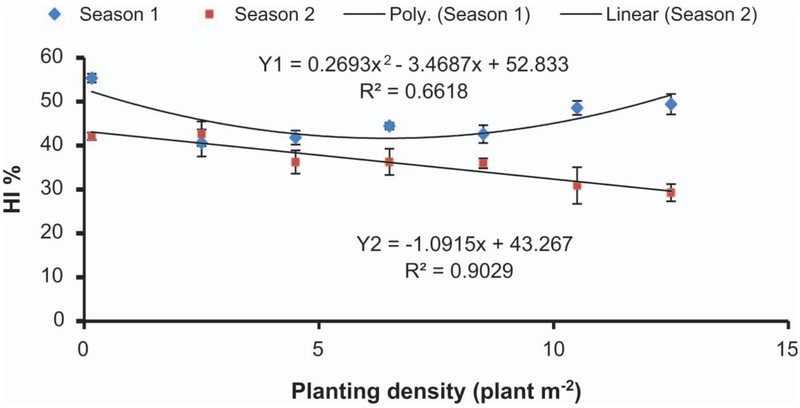

Figure 3. Relationship between planting density and harvest index (HI) in two seasons.

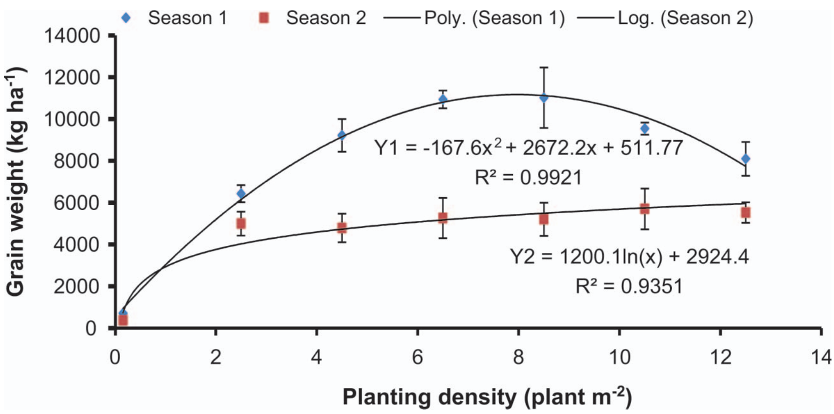

Figure 4. Relationship between planting density and grain weight ha^{-1} in two seasons.

in the second season, HI decreased with increasing planting density (Table 9 and Figure 3). Other researchers have reported different results for the effect of planting density on HI. Contrary to our results, Vega et al. (2000) reported that maize showed high and constant HI values at intermediate planting densities and the value of HI decreased at high and low planting densities. Tollenaar et al. (2006) concluded that crowding stress affected dry matter accumulation but it did not affect HI.

Using the second-year experimental data, the best equations were fitted to show the relationship between planting density and HI for two seasons. In the first season, a quadratic trend was observed and in the second season there was a logarithmic trend between planting density and HI (Table 7 and Figure 3). The equations developed to show the relationship between planting density and HI were tested against the first-year experimental data. The result showed that the developed equations could not predict HI with a high degree of accuracy in either seasons (the high values of RMSE and the low values of *d*) (Table 7).

The interaction between planting density and season had significant effect on grain yield in both years ($p \geq 0.01$). In the first season of 2007, the highest grain yield was obtained at a planting density of 6.5 plants m^{-2}, whereas in the second season, grain yield was the same at planting densities of 4.5 and 6.5 plants m^{-2} (Table 8). Almost the same trend was observed in the second year. In the first season of 2008, maximum grain yield (10,930–11,010 kg ha^{-1}) was observed for the middle planting densities (6.5 and 8.5 plants m^{-2}), whereas in the second season, the grain yield (4780–5700 kg ha^{-1}) was the same at planting densities between 2.5 and 12.5 plants m^{-2} (Table 9). The results showed that increasing planting density could not compensate for yield reduction, which was due to a reduction in the numbers of ears per plant and seeds per ear at higher planting densities. Consequently, a constant grain yield was observed at planting densities between 2.5 and 12.5 plants m^{-2} in the second season. Based on this result, it can be concluded that the planting density should be reduced under stress conditions (in the second season). Other researchers have reported similar results. In central and eastern Nebraska, Larson and Clegg (1999) concluded that a full-season hybrid produced a maximum yield at 8.5 plants m^{-2} if no stress occurred, but populations should be reduced to 4.5–6.5 plants m^{-2} under an unfavorable environment. Norwood and Currie (1996) also found the same trend and reported that the population of a 105-day hybrid planted in early to mid May should not exceed 4.5 plants m^{-2} in southwest Kansas. In the driest year of their study, however, a population of 2.8 plants m^{-2} produced the highest yield.

Using the second-year experimental data, exponential functions were fitted to show the relationship between yield per plant (Y) and planting density (X). ($Y = 416.22 \times \exp^{-0.146X}$; $R^2 = 0.987$) and ($Y = 229.39 \times \exp^{-0.142X}$; $R^2 = 0.955$) were the developed equations for the first and second season, respectively. Although the yield per plant in the two seasons was not the same, the equations showed that the slope of curves in both seasons followed almost the same trend (-0.146 and -0.142). This means that the rate of yield reduction with increasing planting density was similar for both seasons, but the relationship between planting density and yield per unit area followed a quadratic trend in the first season and a logarithmic trend in the second season (Table 7, Figure 4). The equations developed to show the relationship between planting density and grain yield were tested against the first-year experimental data. The result using the developed equation showed that the relationship between planting density and grain yield could predict grain yield with high accuracy in the first season (low value of RMSE: 406 kg ha^{-1} and high value of d: 0.95) (Table 7). But in the second season, the developed equation could not predict grain yield with a high degree of accuracy (high value of RMSE, 1315 kg ha^{-1} and low value of d, 0.72) (Table 7).

Conclusion

Although the experiments were conducted without any water and nutrient limitations in either year, heat stress during the second season caused a reduction in grain yield and yield components. This study found that corn should be planted in the first season as a main crop (mid-April) for higher corn growth and yield in Golestan, Iran with 6.5 plants m^{-2}. To obtain a high grain yield under heat stress conditions (in the second season), the plant population should be decreased to between 2.5 and 4.5 plants m^{-2}.

Under heat stress conditions (in the second season), grain yield and TDM were reduced in both years, but the rate of grain yield reduction was higher than the rate of TDM reduction (Table 4). In accordance with the results of this study, it seems that the goal of corn production should be changed in the second season. It is recommended that corn should be planted at a high planting density (10.5 plants m^{-2}) for forage production rather of grain production in the second season.

The equations developed can be used to predict LAI, TDM and grain yield for the first season with a high degree of accuracy at different planting densities in this region. However, the equations developed for predicting TDM and grain yield cannot simulate their values with a high degree of accuracy in the second season.

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