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Plant Density Effects on Growth, Yield and Yield Components of Two Soybean Varieties under Equidistant Planting Arrangement

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Abstract: Optimum plant density of soybean varies with geographic location and variety. The present study was undertaken with a view to optimize plant density of two soybean varieties using equidistant planting patter to obtain higher yield. The experiments were conducted in three consecutive seasons viz., Rabi 2004-05, Kharif 2005 and Rabi 2005-06 at Mymensingh, Bangladesh with two soybean varieties G-2 and PB-1 and six plant densities viz., 20, 40, 60, 80, 100 and 120 plants m^{-2} established using an equidistant planting pattern of 22.4×22.4 cm, 15.8×15.8 cm, 12.9×12.9 cm, 10.0× 10.0 cm and 9.1× 9.1 cm, respectively. Seed yield increased with increase of plant density up to 80 to 100 plants m^{-2} depending on variety and season. The increase in plant density decreased yield components such as number of pods $plant^{-1}$, seeds pod^{-1} and 100-seed weight as well as seed yield $plant^{-1}$. The soybean seed yield was positively correlated with total dry matter and leaf area index. The present study concludes that the highest soybean yield could be possible with a plant density of 80-100 plants m^{-2} depending upon variety, season and related agronomic management options.

Key words: Canopy closure, total dry matter, leaf area index, crop environment, variety, season

INTRODUCTION

Plant density is an important agronomic factor that manipulates micro environment of the field and affects growth, development and yield formation of crops. Within certain limits, increase of Plant Population Density (PPD) decreases the growth and yield per plant but the reverse occurs for yield per unit area (Caliskan *et al*., 2007). Under the temperate environment of Canterbury, New Zealand, increase of Plant Population Density (PPD) up to 40 plants m^{-2} gave the highest yield but above this PPD no yield advancement was achieved (Rahman *et al*., 2004). The chosen crop spacing is based on the hypothesis that optimal PPD allows interception of all (i.e., ≥95%) of the available Photosynthetically Active Radiation (PAR) to give the highest yield. No further yield advancement with further increase of PPD can occur (Duncan, 1986) because of decrease in radiation use efficiency at higher PPD (Purcell *et al*., 2002).

The optimum plant density to attain highest yield may vary with the genotype and geographical location. In the USA, the optimum plant density varies from 30 to 50 plants m^{-2} (Grichar, 2007). In South Korea, Kang *et al.* (1998) reported the highest yield at 33 to 53 plants m^{-2} while the Cho and Kim, (2010) obtained highest yield at 66 plants m^{-2}. In India, a plant density of 40 to 60 plants m^{-2} was reported to be the optimum for soybean depending on the variety under cultivation (Rani and Kodandaramiah, 1997), while Singh (2010) reported the highest yield with 66 plants m^{-2}. In Turkey, Zaimoglu *et al.* (2004) found the highest yield at 12.8 plants m^{-2} while from the study of Mehmet (2008) it was 29 plants m^{-2}. The optimum plant density reported in Kenya was 45 plants m^{-2} (Misiko *et al*., 2008) while that in Ethiopia was 40 plants m^{-2} (Worku and Astatkie, 2010). In Iran, the highest yield of soybean is obtained at 60 plants m^{-2} (Daroish *et al*., 2005). In Bangladesh, the plant densities of 50 and 60 plants m^{-2} are suggested for kharif II (rainy) and rabi (dry) seasons, respectively (BARI, 2005). The above information explicitly indicates that optimum plant density for soybean could vary depending on geographical location.

Plant density affects yield in soybean by modulating leaf area and therefore, light interception and canopy photosynthesis (Wells, 1991). The narrow row soybean gives higher yield than the wider row soybean because of greater light interception (Board *et al*., 1992). Ibrahim (1996) observed that Leaf Area Index (LAI) and light interception (LI) increased with increasing plant density over a range of 7 to 21 plant m^{-2}. Ball *et al.* (2000) concluded that higher plant population facilitated

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maximum light interception that ultimately helped adding higher Crop Growth Rate (CGR) and Total Dry Matter (TDM) of soybean.

The accumulation of Total Dry Matter (TDM) of a crop depends on its' efficiency in utilizing the radiant energy for net CO_2 assimilation (Gardner *et al*., 1985). The amount of solar radiation interception into the canopy depends on plant arrangement and plant density. Thus it appears that the biomass production of crops is closely related to the amount of solar radiation intercepted by the crop canopy (Rahman *et al*., 2005). The higher plant population speeds up canopy closure (when little or no incoming radiation reaches the soil surface) and increases interception of PAR needed for carbohydrate production in the plants (McKenzie *et al*., 1992).

The effect of plant density on growth, plant characters and yield could vary due to varietal characters and growing seasons in the same geographical areas. Thus the relationship of seed yield with different growth parameters and yield components under variable planting density is very important to understand the basic mechanism of yield-plant density relationship and this would also help in optimizing plant density for improving yield of soybean. Two soybean cultivars such as Shohag (PB-1) and Bangladesh Soybean-4 (G-2) are commercially grown in Bangladesh. These cultivars differ in morphological characters and also in use. Cultivar G-2 is rich in protein and is used as animal feed while PB-1 is suitable as human food. The morphological difference between these cultivars indicates requirement of different plant density for their optimum yield. The research reports in this line are highly scarce under Bangladesh condition and elsewhere. However, the plant density relation with yield of soybean and the underlying principle of this relationship has still been remains as a germane research issue. Therefore, the present study was conducted with a view to find out the optimum the plant densities of two soybean varieties under Old Brahmaputra Floodplain Agroecological zone of Bangladesh.

MATERIALS AND METHODS

Site and soil: Experiments were conducted at Bangladesh Agricultural University (BAU), Mymensingh (Latitude 24°75′ N, Longitude 90°5′ E, Altitude 18 m), during three consecutive soybean growing seasons namely: rabi 2004-05, kharif II 2005 and rabi 2005-06. The rabi and kharif II seasons generally extend from November to March and from July to October, respectively. The site belongs to the Sonatola Soil Series under the Old Brahmaputra Floodplain Agro-ecological Zone (AEZ 9) with Non-calcareous Dark Grey Floodplain soil (UNDP/FAO, 1988). The soil was loam in texture having pH 6.84. The soil contained low organic matter (1.50%), total nitrogen (0.073%), extractractable phosphorus (12.0 mg kg^{-1}), sulphur (9.5 mg kg^{-1}), zinc (0.47 mg kg^{-1}) and medium amount of potassium (0.18%). The soil test result also showed that the amount of P, K, S and Zn were relatively higher in kharif-II season than those in Rabi seasons while the amount of total nitrogen was higher in Rabi season than in kharif-II season. The long-term mean monthly temperature (1983-2003) shows that the temperature in November is 23.9°C but drops to 18.1°C in January and reaches to 24.7°C in March. The temperature in August attains to 29.0°C and then declines to 27.2°C in October. The long-term average total monthly rainfall during November to February was practically zero but slight rainfall occurs in March and April. The rainfall in July is 42.58 cm and that decreases to 19.83 cm in October.

Treatment and design: Two soybean varieties viz., Bangladesh soybean-4 (G-2) and Shohag (PB-1) and six planting densities viz., 20, 40, 60, 80, 100 and 120 plants m^{-2} were included in the trial with a split plot design: varieties were assigned to main plot and plant density into the subplots with three replications. Unit plot size was 4.4×3.0 m. An equidistant square planting pattern having spacing 22.4×22.4 cm; 15.8×15.8 cm; 12.9×12.9 cm; 11.2×11.2 cm; 10.0×10.0 cm and 9.1×9.1 cm, respectively were used to create target plant densities of 20, 40, 60, 80, 100 and 120 plants m^{-2}.

Husbandry: Seed sowing was done on 6 January, 28 July and 3 December 2005, respectively for rabi 2004-05, kharif 2005 and rabi 2005-06 growing seasons by manually placing three seeds per hill at 2-3 cm depth. Prior to sowing, seed was inoculated with *Rhizobium* inoculum collected from Bangladesh Institute of Nuclear Agriculture (BINA). Each unit plot was uniformly fertilized during final land preparation at 23-69-60-16-1 kg ha^{-1} N-P_2O_5-K_2O-S-Zn through urea, triple super phosphate, muriate of potash, gypsum and zinc sulphate (BARC, 2005). Different intercultural operations such as weeding, thinning, gap filling and irrigation were done as and when needed. For example, weeding was done at 20 and 40 DAS in Rabi 2004-05, 20 and 30 DAS in Kharif-II 2005 and 21, 34 and 50 DAS in Rabi 2005-06 seasons followed by thinning to maintain a single seedling at each hill as per experimental specification. Gap filling was done at 42 DAS in Rabi 2004-05 and 35 DAS in Rabi 2005-06 seasons with the additional seedlings of same age raised in a corner of the experimental field and the irrigation was applied at the same day. In Kharif-II 2005 season, gap filling was done twice, first at 30 DAS and second at 37 DAS. In Rabi

2005-06 season, second irrigation was given at 65 DAS because the soil moisture deficit of a plot reached about 50% of the field capacity. The crop was infested by hairy caterpillar in all the three seasons. The rate of infestation was higher in Kharif-II season than Rabi seasons. The hairy caterpillar was successfully controlled with the application of Dimethion 40 EC at 1.5 L ha^{-1} at 65 DAS in Rabi 2004-05, 28, 44 and 56 DAS in Kharif-II 2005 and 61 DAS in Rabi 2005-06 seasons. There was no disease infection in the crop field.

Harvesting and processing: The crop was harvested at full maturity from the central 6.36 m^2 area (2.52×2.52 m) of each plot. In Rabi 2004-05, both the varieties were harvested on 20 April 2005, in Kharif-II 2005, variety G-2 and PB-1 were harvested on 27 October and 14 November 2005, respectively while in Rabi 2005-06, harvesting was done on 1 and 9 April 2006 respectively for variety G-2 and PB-1. After threshing, cleaning and drying, the weight of seed of each plot was recorded at dry weight basis.

Data recording: Data on Leaf Area Index (LAI), Leaf Area Duration (LAD), Total Dry Matter (TDM) and Crop Growth Rate (CGR) were recorded by taking plant samples from randomly selected 0.20 m^2 quadrats in each plot at 10 and 15 day intervals, respectively for Rabi and Kharif-II seasons starting at 30 DAS (excluding border plants and plants of four central rows). Leaf area of the sample plants was measured using a leaf area meter (LI-3000) and LAI was calculated using following equation below. LAD was also calculated by integrating the leaf area index over time.

$$LAI = \frac{\text{Total leaf area of the crop}}{\text{Total ground area under the crop}}$$

After leaf area measurements the whole aboveground plants in each quadrate were dried in a force draft oven at 80°C for 72 h (until constant weight was reached). TDM was recorded on m^{-2} basis and CGR was also calculated from the TDM data using the following equation (Gardner *et al*., 1985) and was expressed in g m^{-2} day^{-1}.

$$CGR = \frac{w_1 - w_2}{t_2 - t_1}$$

where, w_2 is the weight of plants at time t_2, w_1 is the weight of plants at time t_1.

Prior to harvesting 10 randomly selected plants were uprooted from the harvested area of each plot for recording different crop characters (viz., plant height, number of nodes $plant^{-1}$, number of branches $plant^{-1}$) and yield components (viz., number of fertile pods $plant^{-1}$, number of seeds $plant^{-1}$, number of seeds pod^{-1}, weight of 100 seeds and seed yield $plant^{-1}$). The per unit area (m^{-2}) seed yield, stover yield and total dry matter yield as well as harvest index (%) were recorded from the plot harvest of central 6.36 m^2 area. The dry weight of main-stem and branches were recorded after drying the sample in an electric oven at 80°C for 72 h. Seed yield of harvested area of each plot was recorded after proper drying and expressed in g m^{-2} on dry weight basis (i.e., 0% seed moisture content, SMC). The SMC was determined by drying the seed in oven at 130°C for 2 h (until constant weight was reached). Average values of randomly taken 100 seeds in 10 replicates were used to record 100 seed weight. The weight of seed $plant^{-1}$ was also recorded on dry weight basis and this parameter represents the sink capacity of the plant (Oh *et al*., 2007). Stover yield (total weight of main-stem, branch and leaf (when present) and pod shell) was taken after oven drying at 80 °C for 72 h and was expressed in g m 2 on dry weight basis. The total dry matter (biological yield) was recorded as the sum of grain and stover yield. Harvest index was calculated from the ratio of grain yield to the biological yield and was presented as percentage.

Statistical analysis: The data obtained were analyzed following Analysis of Variance (ANOVA) using a split plot design and mean differences were adjudged by Duncan's Multiple Range Test using MSTAT-C statistical analysis software. The regression analysis was done using a statistical package program MINITAB.

RESULTS

Growth parameters: Plant density influenced the Leaf Area Index (LAI), Leaf Area Duration (LAD), Total Dry Matter (TDM) at R5 stage and Crop Growth Rate (CGR) of both the varieties significantly in all the three seasons. All these growth parameters increased with increase of plant density up to a certain density and then declined depending on variety and season (Table 1). The highest LAI and LAD values were attained at the highest density of 120 plants m^{-2}. The highest LAI of variety G-2 in rabi 2004-05, kharif-II 2005 and rabi 2005-06 seasons were 5.05, 1.47 and 4.26 and for variety PB-1 were 5.10, 3.35 and 3.90, respectively. The highest LADs of variety G-2 in rabi 2004-05, kharif-II 2005 and rabi 2005-06 seasons were 110, 56 and 179 days while those for variety PB-1 were 117, 148 and 170 days, respectively. Both TDM and CGR also increased with increase of plant density and the highest values were attained at 100 plants m^{-2} or at 120 plants m^{-2} depending on the season. In rabi 2004-05, both the varieties showed the highest TDM at 120 plants m^{-2}

Table 1: Effect of plant density and cultivar on leaf area index, leaf area duration, total dry matter at R5 stage and crop growth rate of soybean in Rabi 2004-05, kharif-II 2005 and Rabi 2005-06 seasons

	LAI			LAD (days)			TDM (g m^{-2})			CGR (g m^{-2} d^{-1})		
Plant density (Plants m^{-2})	Rabi 2004-05	Kharif-II 2005	Rabi 2005-06	Rabi 2004-05	Kharif-II 2005	Rabi 2004-05	Rabi 2004-05	Kharif-II 2005	Rabi 2005-06	Rabi 2004-05	Kharif-II 2005	Rabi 2004-05
Variety G-2												
20	2.45^{f}	0.19^{i}	2.21^{f}	46.28^{h}	07.77^{i}	066.10^{i}	320.41	096.44^{g}	415.31^{e}	9.49^{i}	01.87^{d}	05.41^{e}
40	2.49^{f}	0.53^{gh}	3.11^{d}	59.02	18.70^{h}	095.68^{h}	390.58	118.25^{g}	696.63^{c}	11.12^{g}	02.17^{d}	09.11^{c}
60	3.69^{d}	0.60^{g}	3.31^{cd}	76.81^{e}	26.04^{g}	134.28^{e}	384.45	146.87^{f}	720.81^{c}	11.63^{f}	03.25^{c}	09.40^{bc}
80	4.18^{c}	0.96^{f}	3.36^{c}	90.39^{d}	37.69^{f}	140.83^{d}	478.39	211.67^{cd}	858.20^{a}	14.28^{ab}	03.28^{c}	11.24^{a}
100	5.01^{a}	1.36^{de}	4.13^{a}	99.55^{c}	50.71^{e}	169.17^{b}	537.07	253.61^{b}	807.66^{ab}	14.37^{a}	04.75^{b}	10.52^{ab}
120	5.05^{a}	1.47^{d}	4.26^{a}	110.19^{b}	56.06	179.08a	622.94	249.78^{b}	727.49c	13.45^{cd}	05.23^{b}	10.22^{abc}
Variety PB-1												
20	1.71^{h}	0.39^{h}	1.61^{g}	35.29^{i}	017.13^{h}	044.87^{j}	261.33	165.89^{ef}	403.61^{e}	8.12^{j}	01.90^{d}	05.28^{e}
40	2.21^{g}	0.90^{f}	1.52^{g}	53.69^{g}	041.91^{f}	062.11^{i}	369.87	189.22^{de}	413.52^{e}	10.2^{3h}	03.47^{c}	05.36^{e}
60	2.80^{e}	1.27^{e}	2.79^{e}	66.63^{f}	053.31^{de}	107.89^{g}	408.33	231.82^{bc}	561.01^{d}	11.28^{fg}	03.16^{c}	07.13^{d}
80	4.08^{c}	2.43^{c}	2.88^{e}	90.95^{d}	098.70^{c}	123.52^{f}	460.85	252.26^{b}	603.11^{d}	13.01^{de}	04.97^{b}	07.79^{d}
100	4.60^{b}	2.64^{b}	3.51^{c}	101.12^{c}	120.94^{b}	147.85^{c}	528.34	425.14^{a}	769.52^{bc}	13.88^{bc}	08.57^{a}	09.97^{bc}
120	5.10^{a}	3.35^{a}	3.90^{b}	117.15^{a}	148.63^{a}	170.16^{b}	609.62	417.22^{a}	752.98^{bc}	12.85^{e}	08.20^{a}	09.70^{bc}
CV (%)	3.59	6.70	4.40	4.47	5.14	4.96	7.38	6.93	6.07	2.023	12.00	07.42
F-test	**	**	**	**	**	**	ns	**	**	*	**	**

Values in a column having same letter (s) do not differ significantly at $p \leq 0.05$ as per DMRT. ns: Not significant

Table 2: Effect of plant density and cultivar on plant height, number of nodes plant^{-1}, number of branches plant^{-1} and number of pods plant^{-1} of soybean in Rabi 2004-05, kharif-II 2005 and Rabi 2005-06 seasons

	Plant height (cm)			No. of nodes plant^{-1}			No. of branches plant^{-1}			No. of pods plant^{-1}		
Plant density (Plants m^{-2})	Rabi 2004-05	Kharif-II 2005	Rabi 2005-06	Rabi 2004-05	Kharif-II 2005	Rabi 2004-05	Rabi 2004-05	Kharif-II 2005	Rabi 2005-06	Rabi 2004-05	Kharif-II 2005	Rabi 2004-05
Variety G-2												
20	83.73^{a}	24.82^{h}	66.23	9.30^{ab}	10.63^{d}	16.10	3.45^{a}	0.83^{c}	5.03^{a}	35.43^{a}	12.67^{e}	91.37^{a}
40	85.07^{a}	25.89^{gh}	74.16	8.97^{bc}	11.00^{cd}	15.97	3.23^{ab}	0.60^{ef}	4.00^{b}	30.27^{c}	12.67^{e}	56.50^{de}
60	85.53^{a}	27.42^{efg}	75.37	8.62^{cd}	11.37^{bc}	16.03	3.20^{bc}	0.73^{d}	3.90^{bc}	23.87^{d}	12.07^{ef}	68.70^{b}
80	85.67^{a}	29.67^{d}	75.90	8.53^{cd}	11.57^{bc}	15.13	3.00^{bcd}	0.67^{de}	3.50^{cd}	20.20^{e}	11.47^{ef}	64.13^{c}
100	86.07^{a}	30.12^{d}	82.17	8.47^{cd}	11.80^{b}	15.57	2.63^{ef}	0.60^{ef}	3.30^{d}	18.17^{f}	11.17^{ef}	54.37^{e}
120	86.02^{a}	28.62^{def}	84.83	8.13^{d}	10.37^{d}	15.77	2.47^{fg}	0.63^{ef}	2.67^{ef}	14.60^{gh}	10.23^{f}	39.77^{f}
Variety PB-1												
20	50.53^{e}	27.22^{fg}	45.16	9.70^{a}	11.00^{cd}	12.60	2.97^{cd}	1.33^{a}	3.10^{de}	32.70^{b}	20.87^{a}	58.30^{d}
40	53.40^{d}	28.91^{de}	49.85	9.40^{ab}	12.47^{a}	12.23	2.77^{de}	1.30^{a}	3.07^{de}	20.03^{e}	19.53^{ab}	38.60^{f}
60	55.07^{d}	29.48^{d}	54.61	7.60^{e}	12.67^{a}	11.80	2.43^{fg}	0.93^{b}	2.17^{gh}	19.00^{ef}	18.63^{bc}	31.57^{g}
80	60.17^{c}	32.38^{c}	55.17	7.07^{f}	12.70^{a}	12.80	2.3^{7g}	0.97^{b}	2.57^{fg}	17.87^{f}	18.33^{bc}	40.13^{f}
100	66.20^{b}	42.58^{a}	59.17	7.03^{f}	12.90^{a}	11.43	2.33^{g}	1.00^{b}	1.97^{h}	15.57^{g}	17.40^{c}	25.10^{h}
120	59.40^{c}	40.70^{b}	59.02	7.01^{f}	12.67^{a}	11.50	2.28^{g}	0.57^{f}	2.37^{fgh}	13.43^{h}	15.53^{d}	29.23^{g}
CV (%)	2.06	2.89	3.02	3.69	3.24	5.02	4.95	5.84	8.08	3.83	7.20	3.06
F-test	**	**	ns	**	*	ns	*	**	**	**	*	**

Values in a column having same letter (s) do not differ significantly at $p \leq 0.05$ as per DMRT. ns: Not significant

(622 g m^{-2} in variety G-2 and 610 g m^{-1} in variety PB-1). In kharif-II 2005, the highest TDM for both variety G-2 (254 g m^{-2}) and PB-1 (425 g m^{-2}) was found at 100 plants m^{-2}. On the other hand, in rabi 2005-06, variety G-2 showed the highest TDM at 80 plants m^{-2} (858 g m^{-2}) while variety PB-1 attained that (770 g m^{-2}) at 100 plants m^{-2}. In both the rabi seasons, the CGR increased with increase of plant density in both the varieties and the highest was found at 100 plants m^{-2} while in kharif-II 2005, the CGR for variety G-2 was noted at 120 plants m^{-2} (5.23 g m^{-2} day^{-1}) but that in variety PB-1 (11.25 g m^{-2}) was attained at 80 plants m^{-2} (Table 1).

Seed yield and related components: Plant density and variety interacted significantly for seed yield and different traits in all the three seasons except for plant height and number of nodes plant^{-1} in Rabi 2005-06 and number of seeds pod^{-1} and seed yield plant^{-} in kharif-II 2005 season. Variety G-2 produced the tallest plant (86.07 cm) in rabi 2004-05 season and variety PB-1 produced the tallest plant (42.58 cm) in kharif-II 2005 season at plant density of 100 plants m^{-2} (Table 2). Variety G-2 produced the highest number of nodes plant^{-1} at 20 plants m^{-2} (9.70) in rabi 2004-05 but at 100 plants m^{-2} (12.90) in kharif-II 2005 season. Although the number of seeds plant^{-1} decreased as plant density increased for both the cultivars in Rabi 2004-05 and 2005-06 seasons, no such a regular trend was evident in kharif-II 2005 season (Table 3). Variety G-2 produced the highest number of seeds pod^{-1} (2.20) in Rabi 2004-05 season at 80 plants m^{-2}

Table 3: Effect of plant density and cultivar on number of seeds plant^{-1}, number of seeds pod^{-1}, weight of 100 seeds and seed yield plant^{-1} of soybean in Rabi 2004-05, kharif-II 2005 and Rabi 2005-06 seasons

	Seeds plant^{-1} (no.)			Number of seeds pod^{-1}			Weight of 100 seeds (g)			Seed yield (g plant^{-1})		
Plant density (Plants m^{-2})	Rabi 2004-05	kharif-II 2005	Rabi 2005-06	Rabi 2004-05	Kharif-II 2005	Rabi 2004-05	Rabi 2004-05	kharif-II 2005	Rabi 2005-06	Rabi 2004-05	kharif-II 2005	Rabi 2004-05
Variety G-2												
20	63.83^{a}	24.82^{d}	204.57^{a}	1.95^{cd}	1.92^{cde}	2.24	4.03^{d}	05.39^{def}	5.83^{fg}	4.24^{a}	1.19	11.57^{a}
40	41.60^{cd}	20.70^{e}	141.73^{c}	2.08^{abc}	1.65^{e}	2.51	3.93^{de}	05.50^{de}	5.94^{efg}	3.73^{b}	1.15	07.41^{de}
60	39.23^{d}	23.57^{de}	156.67^{b}	2.07^{bc}	1.95^{cde}	2.28	3.13^{f}	05.37^{def}	6.42^{e}	2.55^{c}	1.19	09.23^{c}
80	39.17^{d}	23.17^{de}	142.40^{c}	2.20^{a}	2.02^{bcd}	2.22	3.55^{def}	05.05^{f}	6.16^{ef}	2.07^{d}	1.07	08.12^{d}
100	31.73^{ef}	25.87^{d}	113.73^{d}	2.04^{bc}	2.33^{ab}	2.09	3.42^{ef}	05.61^{d}	6.22^{ef}	2.04^{d}	1.25	06.82^{e}
120	28.27^{g}	19.93^{e}	085.70^{f}	2.10^{ab}	1.95^{cde}	2.16	3.43^{ef}	05.10^{ef}	5.48^{g}	1.90^{d}	0.93	03.74^{g}
Variety PB-1												
20	53.33^{b}	34.13^{c}	103.27^{e}	1.51^{h}	1.64^{e}	1.78	7.96^{a}	09.88^{bc}	12.29^{ab}	2.57^{c}	3.07	10.64^{b}
40	51.94^{b}	39.63^{b}	079.27^{f}	1.72^{fg}	2.03^{bcd}	2.06	7.19^{b}	09.76^{c}	11.67^{c}	1.63^{e}	3.47	07.47^{de}
60	43.13^{c}	45.00^{a}	057.77^{g}	1.80^{ef}	2.41^{a}	1.83	5.90^{c}	09.83^{bc}	12.38^{a}	1.23^{fg}	3.74	05.86^{f}
80	33.90^{e}	33.43^{c}	078.40^{f}	1.68^{fg}	1.83^{de}	1.95	6.13^{c}	09.56^{c}	11.17^{d}	1.39^{f}	3.19	06.70^{e}
100	29.80^{fg}	37.93^{b}	046.60^{h}	1.64^{g}	2.19^{abc}	1.86	6.85^{b}	10.20^{ab}	10.82^{d}	1.08^{gh}	3.19	04.09^{g}
120	27.43^{g}	32.73^{c}	050.30^{gh}	1.88^{de}	2.11^{ad}	1.72	6.94^{b}	10.38^{a}	11.86^{bc}	0.97^{h}	3.01	05.30^{f}
CV (%)	3.62	7.08	5.09	3.89	8.78	5.23	5.69	2.86	3.12	5.03	8.49	5.72
F-test	**	**	**	*	**	ns	**	*	**	**	ns	**

Values in a column having same letter (s) do not differ significantly at $p \leq 0.05$ as per DMRT. ns: Not significant

Table 4: Effect of plant density and cultivar on seed yield, stover yield, total dry matter and harvest index of soybean in Rabi 2004-05, kharif-II 2005 and Rabi 2005-06 seasons

	Seed yield (g m^{-2})			Stover yield (g m^{-2})			Total dry matter (g m^{-2})			Harvest index (%)		
Plant density (Plants m^{-2})	Rabi 2004-05	Kharif-II 2005	Rabi 2005-06	Rabi 2004-05	kharif-II 2005	Rabi 2005-06	Rabi 2004-05	kharif-II 2005	Rabi 2005-06	Rabi 2004-05	kharif-II 2005	Rabi 2005-06
Variety G-2												
20	61.91^{f}	34.63^{g}	122.86^{de}	115.48^{fg}	19.71^{e}	270.80^{b}	177.38^{gh}	054.33^{j}	393.65^{c}	34.90^{a}	63.71^{a}	31.23^{g}
40	109.93^{c}	34.91^{g}	148.91^{c}	208.92^{e}	50.24^{d}	278.69^{b}	318.85^{e}	083.75^{i}	427.59^{b}	34.55^{a}	40.06^{g}	34.84^{cd}
60	114.03^{bc}	50.10^{f}	157.78^{b}	237.98^{d}	53.83^{d}	280.87^{b}	352.01^{cd}	103.93^{h}	438.65^{b}	32.40^{ab}	48.20^{ef}	35.99^{bc}
80	119.50^{b}	83.58^{d}	185.22^{a}	283.53^{c}	100.48^{b}	298.31^{a}	403.03^{b}	184.06^{e}	483.53^{a}	29.69^{bc}	45.42^{f}	38.31^{a}
100	148.85^{a}	52.93^{f}	126.75^{d}	358.43^{a}	86.83^{c}	266.59^{b}	507.28^{a}	139.76^{f}	393.33^{c}	29.35^{c}	37.87^{gh}	32.21^{fg}
120	144.91^{a}	48.15^{f}	112.99^{f}	380.62^{a}	84.57^{c}	251.10^{c}	525.54^{a}	132.72^{fg}	364.09^{de}	27.58^{cd}	36.23^{h}	31.05^{g}
Variety PB-1												
20	48.58^{g}	72.76^{e}	88.33^{h}	100.77^{g}	53.75^{d}	148.57^{g}	149.35^{h}	126.51^{g}	236.90^{h}	32.62^{ab}	57.52^{b}	37.29^{ab}
40	57.88^{f}	84.58^{d}	102.90^{g}	133.81^{e}	57.43^{d}	170.92	191.70^{g}	142.01^{f}	273.82^{g}	30.18^{bc}	59.52^{b}	37.58^{ab}
60	72.18^{e}	114.67^{c}	112.62^{f}	204.17^{f}	86.91^{c}	217.27^{e}	276.36^{f}	201.58^{b}	329.89^{f}	26.10^{d}	56.93bc	34.13^{de}
80	82.71^{d}	117.94^{c}	116.67^{ef}	243.49^{d}	102.29^{b}	232.82^{d}	326.20^{de}	220.23^{c}	349.49^{e}	25.35^{d}	53.55cd	33.40^{def}
100	77.40^{de}	151.06^{a}	126.67^{d}	299.39^{c}	143.77^{a}	243.33^{cd}	376.79^{bc}	294.83^{a}	370.00^{d}	20.55^{e}	51.23de	34.23^{d}
120	72.59^{e}	144.16^{b}	115.34^{ef}	330.17^{b}	140.29^{a}	240.11^{cd}	402.76^{b}	284.45^{b}	355.46^{de}	18.03^{e}	50.67de	32.45^{efg}
CV (%)	4.70	4.75	3.43	6.08	4.80	3.31	5.20	3.69	2.57	5.74	4.04	2.74
F-test	**	**	**	*	**	**	**	**	**	**	**	**

Values in a column having same letter(s) do not differ significantly at $p \leq 0.05$ as per DMRT

but variety PB-1 produced the lowest (1.51) at 20 plants m^{-2}. In kharif-II 2005 season variety PB-1 produced the highest number of seeds pod^{-1} (2.41) at 60 plants m^{-2} but the lowest was obtained in cultivar PB-1 (1.64) at 20 plants m^{-2} (Table 2). Variety PB-1 produced the seed with highest weight of 100 seeds (7.96 g) at 20 plants m^{-2} in *rabi* 2004-05, at 120 plants m^{-2} (10.38 g) in kharif-II 2005 season and at 60 plants m^{-2} (12.38 g) in Rabi 2005-06 season. Both the varieties produced the heaviest seed in rabi 2005-06 season among the three seasons (Table 3). Variety G-2 produced the highest stover yield (380.62 g m^{-2}) at 120 plants m^{-2} and variety PB-1 produced the lowest (100.77 g m^{-2}) at 20 plants m^{-2} in Rabi 2004-05 season (Table 4). In kharif-II 2005 season, variety PB-1 produced the highest stover yield (143.77 g m^{-2}) at 100 plants m^{-2} which was at par with 120 plants m^{-2}, while variety G-2 at 20 plants m^{-2} produced the lowest (19.71 g m^{-2}). Variety G-2 produced the highest (298.31 g m^{-2}) stover yield at 80 plants m^{-2} in Rabi 2005-06 season, while variety PB-1 produced the lowest (148.57 g m^{-2}) at 20 plants m^{-2} (Table 4). Variety G-2 produced the highest TDM (525.54 g m^{-2}) at 120 plants m^{-2} while variety PB-1 produced the lowest (149.35 g m^{-2}) at 20 plants m^{-2} in Rabi 2004-05 season (Table 4). On the other hand, in kharif-II 2005 season, the highest TDM (294.83 g m^{-2}) was found in cultivar PB-1 at 100 plants m^{-2} and the lowest (54.33 g m^{-2}) in cultivar G-2 at 20 plants m^{-2}. In Rabi 2005-06 season, the highest TDM (483.53 g m^{-2}) was produced by variety G-2 at 80 plants m^{-2} while the lowest (236.90 g m^{-2}) was observed in variety PB-1 at 20 plants m^{-2} (Table 4). In Rabi 2004-05 season, variety G-

2 showed the highest HI (34.90%) at 20 plants m^{-2} which was identical with those for variety G-2 at 40 and 60 plants m^{-2} and variety PB-1 at 20 plants m^{-2}. In kharif-II 2005 season, the highest harvest index (63.71%) was observed in variety G-2 at 20 plants m^{-2} and the lowest (36.23%) by variety G-2 at 120 plants m^{-2} (Table 4). In Rabi 2005-06 season, the highest harvest index (38.31%) was observed in variety G-2 at 80 plants m^{-2} that was at par with variety PB-1 at 20 and 40 plants m^{-2}. On the other hand, the lowest HI (31.05%) was obtained in variety G-2 at 120 plants m^{-2} that was identical with variety PB-1 at 120 plants m^{-2} (Table 4). Thus it appears that variety G-2 performed better in rabi seasons while variety PB-1 in kharif-II season. Variety G-2 and PB-1 gave highest yields at 80 and 100 plants m^{-2}, respectively.

Seed yield relationships with growth and yield related parameters: Seed yield was positively related with Leaf Area Index (LAI), Leaf Area Duration (LAD), Total Dry Matter accumulation (TDM) both at R5 stage and at harvest and Crop Growth Rate (CGR) in all the experiments (Table 5). The correlation coefficients for seed yield with these growth parameters were significant for all the seasons although LAD was not significant only in Rabi 2004-05 season. HI (%) showed positive relationship in all the three seasons but that was significant only in kharif-II 2005 season. All other crop characters and yield components showed either positive or negative relationship with seed yield but the relationship was not consistent for the three seasons (Table 6). For example, plant height showed significant negative relationship with seed yield in Rabi 2004-05 but the relation was highly significant and positive in other two seasons. Similar result was observed for number of nodes $plant^{-1}$, branches $plant^{-1}$, fertile pods $plant^{-1}$, number of seeds $plant^{-1}$ and number of pods $plant^{-1}$. On the other hand, weight of 100-seed showed highly significant positive relationship in Rabi 2004-05 and *kharif-II* 2005 seasons but the relationship was negative and significant in Rabi 2005-06 season (Table 6). Therefore, TDM (both at R5 stage and at harvest), LAI and CGR are the traits which gave consistent relationship with seed yield.

Table 5: Correlation coefficients of relationship of seed yield with different growth parameters of soybean as influenced by plant density in three consecutive seasons

Seasons	LAI	LAD (days)	TDM at R5 stage	CGR	TDM at harvest
Rabi 2004-05	0.420*	0.535**	0.492**	0.415*	0.860**
Kharif II 2005	0.820**	0.858**	0.838**	0.735**	0.967**
Rabi 2005-06	0.382*	0.308ns	0.642**	0.637**	0.927**

*, **Significant at 5 and 1% level and ns: Not significant, n = 36

DISCUSSION

Seed yield $unit^{-1}$ area increased with an increase of plant density up to a certain level and then decreased with further increase in plant density in both the cultivars for all the three seasons. Variety G-2 produced the highest yield at 100 plants m^{-2} in rabi 2004-05 while at 80 plants m^{-2} in Rabi 2005-06 and Kharif-II seasons. On the other hand, cultivar PB-1 exhibited the highest yield at 80 plants m^{-2} in rabi 2004-05 season but at 100 plants m^{-2} in kharif-II 2005 and rabi 2005-06 seasons. The present result implicated that the yield response of soybean to plant density could vary with season and variety.

In all the three seasons, the yield contributing characters such as number of pods $plant^{-1}$, seed $plant^{-1}$, seeds pod^{-1} and 100-seed weight decreased with increase of plant density while the highest seed yield was attained at higher plant density in all the three seasons. The relationships of seed yield per unit area with these yield parameters were not consistent and vary widely among the seasons while all the growth parameters showed significant positive relationship with yield indicating. The strong significant positive correlation of TDM at R5 stage and also at harvest with seed yield indicates that dry matter accumulation per unit area is the major yield determinant in soybean.

Rahman *et al*. (2004) also found significant positive relationship of TDM at seed initiation stage (R5-stage) in soybean and the minimum threshold TDM is 500 g m^{-2} (Egli *et al*.,1987). Wells (1993) supported the hypothesis of Egli *et al*. (1987) and found that the high yield of soybean was possible with the environment that resulted in production of TDM above 500 g m^{-2}. In the present study the highest seed yield of 185 g m^{-2} was obtained with the crop that produced around 483 g m^{-2} which was below the threshold TDM and therefore, it was possible to increase yield with increase of TDM to a threshold level. Thus, present study suggests that TDM at R5 can be considered as an indicator of seed yield in soybean.

Table 6: Correlation coefficients of relationships between seed yield and different yield related traits in soybean as influenced by plant density in three consecutive seasons

Seasons	Plant height	Nodes $plant^{-1}$	Branches $plant^{-1}$	Fertile pods $plant^{-1}$	Seeds $plant^{-1}$	Seeds $pods^{-1}$	Weight of 100 seed	HI
Rabi 2004-05	-0.568**	-0.082^{ns}	-0.794**	-0.331*	-0.526**	-0.409*	0.577**	0.108^{ns}
Kharif II 2005	0.861**	0.827**	0.222^{ns}	0.557**	0.462**	-0.104^{ns}	0.768**	0.604**
Rabi 2005-06	0.602**	0.500**	0.358*	0.368*	0.477**	0.593**	-0.619**	0.283^{ns}

*, ** Significant at 5% and 1% level and ns: Not significant, n = 36

Wells (1991) reported that the crop that could reach canopy closure prior to seed development contributes to high TDM production and seed yield. Although light interception was not measured in the present study, a study at Canterbury, New Zealand confirms that the crop at higher plant densities reached the canopy closure before the start of seed filling and thus contributed to high yield than those at low PPD (Rahman *et al*., 2005). Total dry matter accumulation in crop is dependent on solar radiation interception. Solar radiation interception depends on the leaf area development and incident radiation as reported by previous workers (Willcott *et al*., 1984). The leaf area development regulates the TDM accumulation though interception of solar radiation (Rahman *et al*., 2005). Ball *et al*. (2000) suggested that crop yield per unit area becomes highly constrained at a plant density where canopy closure is not reached by the mid reproductive development stage. Thus canopy closure at early reproductive stage is essential to higher solar radiation interception and higher yield. The yield increase per unit area in response to plant density was because of increase of number of plants per unit area that facilitated early canopy closure (Christmas, 2002; Yilmaz, 2003). Thus it may be concluded that the plant population that facilitates canopy closure at early reproductive stage could be considered as the optimum PPD for achieving high yield in soybean.

Increase of PPD decreased the number of branches plant^{-1} in the present study which supports the previous reports (Reddy *et al*., 1999; Rahman *et al*., 2004; Blumenthal *et al*., 1988). Plants at higher densities accumulate less carbon which is not sufficient to support more branching (Reddy *et al*., 1999). Number of pods plant^{-1} and seed yield plant^{-1} also decreased with increase of plant densities. This may be explained by the fact that Per plant Light Interception (PPLI) is less at higher PPD which results in per plant lower carbon fixation that reduces the plant's ability in carbon assimilation and translocation towards new branch production and thus potentially reduces the growth rates, size of plant organs and node addition rates (Harper, 1977).

Plant height increased with increase in plant density up to a Plant Population Density (PPD) of 100 plants m^{-2} and then declined with further increase in PPD in all the three seasons in both the varieties in the present study. Similar response of plant height to plant density has been reported by Rahman *et al*. (2004). They found that plant height increased with a PPD up to 40 plants m^{-2}, then declined with further increase of PPD. The increase in plant height at higher PPD is probably caused through stem elongation (Reddy *et al*., 1999; Pendersen and Lauer, 2003) and increase of number of nodes plant^{-1} (Oh *et al*., 2007) due to mutual shading (Dominguez and Hume, 1978), while decrease of plant height above the optimal PPD is caused by inter plant competition for growth factors such as moisture, light and nutrients (Chanprasert, 1988). The increase in plant density increases node length as well as the lowest pod height (Mehmet, 2008). The increase the lowest pod height facilitates mechanical harvesting with significant reduction in harvest loss (Grabau and Pfeiffer, 1990; Christmas, 2002; Edwards and Purcell, 2005) and thus increased plant population could be a useful management approach for mechanical harvesting with reduced harvest loss.

Plant height and number of branches plant^{-1} influence the canopy closure and therefore, they contribute to light interception. The high density crops facilitate more light interception at earlier stage of crop growth than the more sparsely grown plants at lower densities. The widely spaced plants cannot take advantage of the increased light interception at the early growth stage of the crop compared to high PPD crops because of incomplete canopy closure. Although per plant growth and yield components increased at lower densities, per unit area yield decreased as a result of less per unit area canopy photosynthesis and dry matter accumulation (Rahman *et al*., 2004). Thus, the insufficient development of the canopy of leaves at earlier reproductive phase at lower densities limits yield (Edwards *et al*., 2005; Ball *et al*., 2000).

In Bangladesh soybean is grown at plant densities of 66 and 50 plants m^{-2} in rabi and kharif-II seasons, respectively (BARI, 2005). These densities are far below than the optimum density found in the present study. Moreover, rabi 2004-05 crop required higher plant density than rabi 2005-06 crop to obtain the highest yield. This variation was probably was related to loss of leaves due to sudden heavy infestation by the hairy caterpillars during the seed development stage in Rabi 2004-05 season. The loss of leaf might have affected the current photosynthate available for seed development in rabi 2004-05 season which was manifested by substantial reduction in seed size than other two seasons. Thus due to the decrease in seed size increased plant density was required to obtain the highest yield in Rabi 2004-05. The lower yield in kharif-II 2005 was probably related to poor canopy development because of shorter plants suggesting the need of higher PPD to achieve full canopy closure (Rahman *et al*., 2004) for achieving maximum yield. The lower plant growth in kharif-II 2005 season was probably associated with heavy rainfall as well as severe weed infestation. Thus, the present study suggests that the season, variety and crop management options are very important determinant of optimum plant density in soybean.

The average soybean yield in the USA is 284 g m^{-2} and in Brazil is 231 g m^{-2} (FAO, 2004) while that in Bangladesh (120 g m^{-2}) is only about half the average yield in the USA and Brazil. The lower yield is not related to cultivar yield potential because the same cultivar was capable of producing about 400 g m^{-2} seed yield in farmers' field in Bangladesh (Woodruff, 1998). Therefore, the yield level of soybean in Bangladesh can easily be improved by manipulating plant density. The establishment of an optimum plant density depends on many agronomic factors such as time of sowing, fertilizer, moisture and pest management for different geographic locations. The optimum leaf area index for soybean varies between 3.4-.-3.6 (Rahman *et al*., 2004) and this should be achieved by early reproductive stage of the crop to attain canopy closure and maximum light interception for ensuring higher dry matter accumulation and thus higher yield. The decision on the optimum plant density for maximum yield, thus, depends on the climate and agronomic management options available for the soybean variety used in a specific geographic area.

Seasonal comparison shows that Rabi season crop produced higher TDM at R5 than kharif-II season crop for both the varieties. The higher TDM in Rabi seasons was probably attributed to the higher LAI and CGR than those in kharif-II season. Crop Growth Rate (CGR) per unit area is highly dependent on the amount of light intercepted by the crop canopy (Ball *et al*., 2000). Nevertheless, yield and dry matter accumulation depend on the amount of solar radiation intercepted by the crop. However, the photosynthetic limit to dry matter accumulation due to insufficient plant population to attain canopy closure may ultimately limit yield of soybean.

CONCLUSION

Present study reveals that soybean seed yield depends on plant density, season and cultivar. Crop dry matter accumulation and leaf area index showed significant positive relationship with seed yield. In the present trial the highest soybean yield was achieved at 80 to 100 plants m^{-2} depending on variety and season. However, the present study concludes that the highest soybean yield could be achieved by ensuring a plant population that helps attaining canopy closure at early stage of reproductive growth depending on season, cultivars and agronomic managements.

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