Agronomic Response of Soybean Varieties to Plant Population in the Guinea Savannas of Nigeria

Alpha Y. Kamara,* Sylvester U. Ewansiha, Steve Boahen, and Abdullahi I. Tofa

ABSTRACT

The agronomic responses of three contrasting soybean [*Glycine max* (L.) Merr.] varieties to plant populations were examined in two distinct agro-ecological locations (at Samaru Zaria and Samaru-Kataf), both in the Guinea savanna of northern Nigeria in 2009, 2010, and in 2011 growing seasons. Three soybean varieties: TGx1835-10E, TGx1904-6F, and TGx1448-2E differing in maturity duration (early, medium, and late maturing, respectively), were evaluated at four plant populations (266,700, 333,300, 533,300, and 666,700 plants ha^{-1}) using a split plot arrangement in randomized complete block design with three replications. The plant populations were the main plots, whereas varieties were subplots. The proportion of intercepted photosynthetically active radiation (IPAR) and leaf area index (LAI) increased with increasing plant population at both locations, indicating that high leaf area indices and high degree of canopy closure at higher plant population intercepted more light than the canopy at lower population and subsequently resulted in relatively high grain and fodder yields. At both locations, optimum plant populations ranged from 533,300 to 666,700 plants ha^{-1} across the years. The northern Guinea savanna location (Samaru Zaria) produced more pods m^{-2}, grain yield, and fodder at higher plant populations than that at the southern Guinea savanna (Samaru-Kataf). Varieties TGx1448-2E and TGx1904-6F intercepted higher proportion of IPAR had higher LAI and produced a greater number of pods m^{-2}, seeds m^{-2}, grain yield, and fodder than TGx1835-10E at both locations in years of good rainfall. These data suggest that soybean yields in the Guinea savanna of northern Nigeria can be increased using higher plant populations than those currently recommended.

Soybean is one of the most important leguminous crops grown in the cropping systems of most tropical countries. Its cultivation is increasing in the savannas of Nigeria for several reasons. It is becoming a major food and cash crop and is widely used in the food and feed industry (Brader, 1998; Sanginga et al., 2002). It contributes to improving soil fertility and reducing *Striga* infestation on farmers' fields (Sanginga et al., 2002; Franke et al., 2004). The International Institute of Tropical Agriculture's (IITA) soybean improvement work in Africa started in the mid-1970s, mainly to increase productivity, which was 0.5 Mg ha^{-1} (Tefera et al., 2010). Other major constraints to soybean production that necessitated IITA's intervention were low seed viability from harvest to the next planting season, poor nodulation of soybean cultivars with the indigenous *Rhizobium* spp., pod shattering, and foliar diseases such as frogeye caused by *Cercospora sojina* and bacterial pustule caused by *Xanthomonas axonopodis* pv. glycines. Over the years, significant progress has been made to overcome some of the major constraints and has improved soybean yields across most of the soybean-producing countries in Africa. The development of adapted freely nodulating tropical germplasm and its distribution to various African countries helped to increase soybean production in Africa. Average yield of soybean in Africa increased to 1.1 Mg ha^{-1} by 2008 (FAO, 2010). Due to the high cash value and relative ease of cultivation, soybean production in Nigeria is steadily increasing. Nigeria alone accounted for 43% of Africa's total production in 2008 (Tefera et al., 2010). Farmers have adopted new varieties developed by IITA (Okogun et al., 2004) that store well and unlike cowpea [*Vigna unguiculata* (L.) Walp.], soybean does not need expensive pesticides to control pests and diseases. They also nodulate freely with native rhizobia strains and supply a large proportion of their N requirement through biological N fixation (Okogun et al., 2004) without depleting soil N reserves (Singh et al., 2003). Despite the rapid increase in soybean production in Nigeria, average soybean yield nationwide is estimated at 1.2 Mg ha^{-1} (FAOSTAT, 2012). The low yields are due in part to limited use of P fertilizer (Kamara et al., 2008) and poor crop management practices including low plant populations.

Farmers in northern Nigeria plant grain crops in rows spaced 75 cm. All tractor and animal mounted ridgers available have a fixed width of 75 cm, leaving the farmers with no option to reduce the row spacing. Farmers can, however, manipulate the

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Abbreviations: ANOVA, analysis of variance; IITA, International Institute of Tropical Agriculture; IPAR, intercepted photosynthetically active radiation; LAI, leaf area index; PAR, photosynthetically active radiation; SED, standard error of the difference; WAP, weeks after planting.

intra-row spacing to suite the various row crops. Maize and cowpea are traditionally planted at 20 to 25 cm between plants as the recommended practice. In Nigeria, farmers are advised to drill soybean at a spacing of 5 cm between plant stands, which corresponds to a population of 266,667 plants ha^{-1}. Most farmers, however, plant soybean at wider spacing similar to maize (*Zea mays* L.) or cowpea, resulting in low populations and subsequently low grain yields. Madanzi et al. (2012) listed low plant population as one of the factors limiting soybean production among smallholder farmers in Zimbabwe. Effect of plant densities on soybean yield is not well understood by farmers. Plant density is an important component of yield in soybean and it is important to determine the optimum plant population for different areas since the areas have different potential for soybean growth. Bilal et al. (2009) stated that the optimum plant density with proper geometry of planting is dependent on variety, its growth habit, and agro-climatic conditions. Ismail and Hall (2000) observed a decrease in grain yield of cowpea with increased spacing. Adjusting planting density is an important tool to optimize crop growth and the time required for canopy closure, and to achieve maximum biomass and grain yield (Liu et al., 2008). Ball et al. (2000) reported that increasing plant populations reduced yield of individual plants but increased yield per unit area. In contrast to maize and cowpea, the ability of soybean to compensate for low population has resulted in little or no response to changes in plant population in some environments. Carpenter and Board (1997) attributed soybean yield compensation at low densities to increased branch dry matter, which increased nodes and reproductive nodes per square meter. This, in turn, results in greater pod and seed numbers per square meter, whereas others reported that pods per plant and seeds per plant were the source of compensation (Ball et al., 2000; Board et al., 1990; Norsworthy and Shipe, 2005). In Arkansas, Ball et al. (2001) showed that for early-planted soybean, population densities contributed less to yield because plants at low plant densities compensated by producing a large number of fertile nodes per plant and pods per fertile node. In contrast, high population densities at late planting compensated for the decreased potential for fertile node production by individual plants. The desire of a soybean farmer is to plant soybean at a population that gives optimal yield. Optimum or minimum plant population for optimum soybean yield is also dependent on growing conditions (Board and Kahlon, 2013). According to De Bruin and Pedersen (2008a), optimal plant population for soybean is lowest when growing conditions are favorable. Under favorable growing conditions, optimum soybean yield can be achieved at low plant populations, whereas a higher plant population is needed to attain optimum yield under poor growing conditions (Wells, 1993). Ball et al. (2000) demonstrated that a shortening photoperiod and higher temperatures curtailed the vegetative growing period and reduced crop biomass of soybean and suggested that higher plant populations than traditionally recommended would optimize grain yield under short-season production system in the mid-south United States. In the West African savannas, where photoperiods are short and temperatures are high, soybean may have to be planted at high populations to obtain optimum yield.

Over the years, several soybean varieties have been released in Nigeria and are still being grown at the recommended population of 266,700 plants ha^{-1}. There is currently no available information on the responses of the new soybean varieties released recently in Nigeria to plant populations. Information on optimum plant population for these varieties may contribute to closing the yield gap of soybean in the Nigeria savannas. The objective of this study was to determine the responses of soybean cultivars with varying maturity duration to plant population in two distinct agro-ecological locations of northern Nigeria.

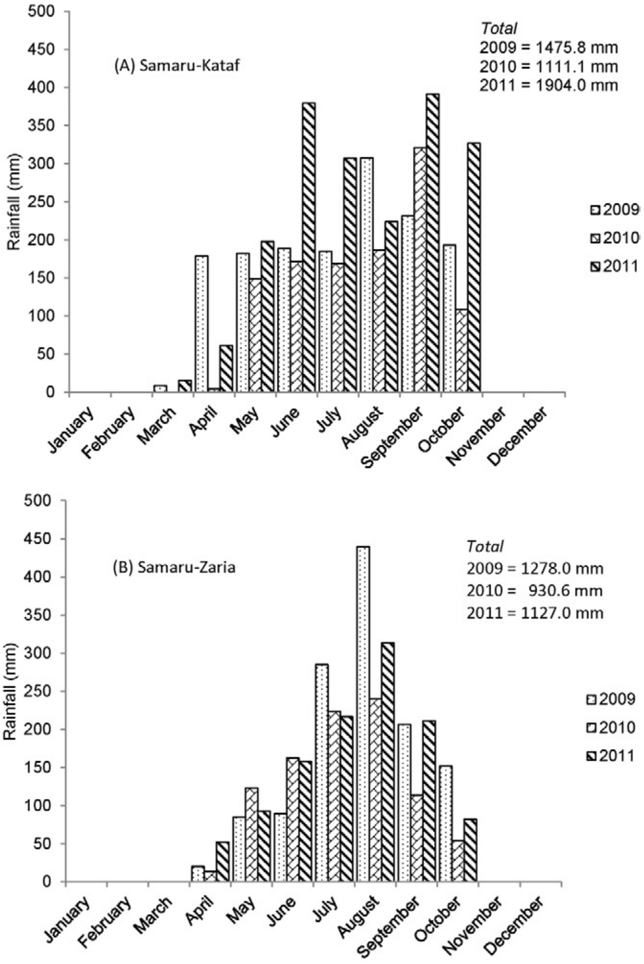

Fig. 1. Rainfall at Samaru-Kataf and Zaria during the experimental period.

MATERIALS AND METHODS

Experimental Site

Field studies were conducted during the 2009, 2010, and 2011 growing seasons at Samaru Zaria (11°11′ N, 7°38′ E) in the northern Guinea savanna and Samaru-Kataf (09°45′ N, 8°22′ E) in the southern Guinea savanna. Composite soil samples were collected from each of the sites and analyzed for soil texture, organic C, N, P, K, and pH according to IITA procedures (IITA, 1982). The results showed that in Samaru Zaria, the soil had 464.0 g kg^{-1} sand; 360.0 g kg^{-1} silt; 176.0 g kg^{-1} clay; organic C of 6.3 g kg^{-1}; N, 0.60 g kg^{-1}; P, 2.0 g kg^{-1}; K, 0.16 cmol kg^{-1}; and pH 5.6. In Samaru-Kataf, the soil had 664.0 g kg^{-1} sand; 140.0 g kg^{-1} silt; 196.0 g kg^{-1} clay; organic C of 5.7 g kg^{-1}; N, 0.46 g kg^{-1}; P, 7.6 g kg^{-1}; K, 0.13 cmol kg^{-1}; and pH 4.6. Rainfall in Samaru Zaria was 1278.0 mm in 2009, 930.6 mm in 2010, and 1127.0 mm in 2011; Samaru-Kataf had 1475.8 mm rainfall in 2009, 1111.1 mm in 2010, and 1904.0 mm in 2011(Fig. 1). In Samaru-Zaria, mean daily average maximum temperature was

32°C with average minimum temperature of 24°C. In Samaru-Kataf, mean daily average maximum temperature was 30°C with average minimum temperature of 22°C.

Soybean Cultivars, Plant Population, and Experimental Design

Three soybean cultivars (early, medium, and late maturing soybean) and four soybean plant populations were compared in the study. The experimental design was a randomized complete block in a split-plot arrangement with four replications. The early cultivar was TGx1835-10E, the medium maturing cultivar was TGx1904-6F, and the late variety was TGx1448-2E. These cultivars were developed by IITA. Four soybean populations were planted 266,700, 333,300, 533,300, and 666,700 plants ha^{-1}. The main plot consisted of soybean. The soybean cultivars were assigned to the subplot. The subplots were 3 by 5 m and consisted of four rows with 0.75 m spacing between rows and intra-row spacing of 5, 10, or 20 cm with varied number of plants per stand to obtain the desired population.

Cultural Practices

The field was disc-harrowed and ridged before planting. Plots were overseeded and then thinned to the respective plant populations of 266,700 plants ha^{-1}, 333,300 plants ha^{-1}, 533,300 plants ha^{-1}, and 666,700 plants ha^{-1}. Seeds of the soybean cultivars were planted at a depth of 3 cm. For populations with four or five plants per stand, eight seeds were planted and later thinned to four or five plants per stand. For the population with one plant per stand, four seeds were planted and later thinned to one plant per stand. Thinning was performed 2 weeks after planting (WAP). At planting, 50 kg of P_2O_5 in the form of SSP was applied. A mixture of pendilin (500 g L^{-1} pendimethalin manufactured by Meghmani Industries Limited, India) and gramaxone (1:1-dimethyl-4, 4-bipyridinum dichloride, manufactured by Syngenta Crop protection AG, Switzerland) at a rate of 1 L ha^{-1} each was applied immediately after planting using a knapsack sprayer. This was followed by hoe weeding just before flowering.

Measurements

The two middle rows were used for data collection. Leaf area index (LAI) and intercepted photosynthetically active radiation (IPAR) were measured at R2 stage according to the method of Fehr and Caviness (1977) using AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, Pullman, WA). Five measurements of incident PAR above the soybean canopy were taken from each plot and averaged. Intercepted PAR was measured under the soybean canopy for each plot. The sensor was placed diagonally across the two inner rows on the soil surface below the soybean canopy so that the two ends of the sensor were in line with the soybean rows. Five measurements were also taken and the displayed average recorded. Measurements were made under cloud-free conditions between 1200 and 1400 h. The percentage of PAR intercepted by the soybean canopy was calculatedas:

$$\text{IPAR} = [1.0 - (\text{PARb}/\text{PARa})] \times 100$$

where IPAR = intercepted PAR; PARa = PAR, µmol m^2 s^{-1}, measured above soybean canopy; and PARb = PAR measured below soybean canopy.

At maturity, all the plants in a quadrat measuring 1.5 m^2 placed across the two middle rows were harvested to calculate number of pods m^{-2} and number of seeds m^{-2}. For grain yield determination, pods on plants from the two middle rows were harvested, sun-dried, and hand-threshed. The grains from the two middle rows were added to those from the quadrat and weighed to calculate grain yield. The moisture content of grain samples from each plot was determined using Farmex MT-16 grain moisture tester. Grain yield kg ha^{-1} was calculated based on 13% moisture content.. For fodder yield determination, leaves and stems from the total net plot were rolled up together and left on the plot to sun-dry to a constant weight. The weight of the dry fodder was added to that of the subsample oven-dried leaf and stem to obtain fodder yield per net plot. This was converted to fodder yield in kg ha^{-1}.

STATISTICAL ANALYSIS

Combined analysis of variance (ANOVA) across years was performed for each location using the PROC Mixed procedure of SAS (SAS Institute, 2011). Block was treated as a random effect whereas year, plant population, and soybean cultivars and their interactions were considered as fixed effects in determining the expected mean square and appropriate *F*-test. Means were separated using LSMEANS statement of PROC Mixed code of SAS with option pdiff at $P \leq 0.05$. The statement calculates the difference between two means and the standard error of the difference (SED). The option calculates the *P* value for the comparison of the difference between two means according to LSD(0.05).

RESULTS AND DISCUSSIONS

Year, population, and variety significantly influenced the agronomic performance of soybean at both locations. Except for IPAR, there were significant interactions among year, variety, and population for all parameters measured (Table 1), suggesting that the varieties responded to population differently in each year. This suggests that soybean response to population may be dependent on the environment. Rainfall varied among the 3 yr at the two locations. At both locations, rainfall was lower in 2010 than in the other years (Fig. 1). This is in agreement with Taylor (1980), who suggested that soybean responds differently to different environmental conditions leading to differences in crop performance.

Intercepted PAR increased with increased population at both locations. Significant increases were recorded in Samaru Zaria for all populations above 266,700 plants ha^{-1} (Table 2). In Samaru-Kataf a significant increase was only recorded for a plant population of 666,700 plants ha^{-1} (Table 2). Our result is consistent with Purcell et al. (2002), who reported that increasing population increased the total accumulation of PAR for soybean during the growing season. The increases may be due to high leaf area indices and high canopy closure, which intercepted more light than the canopy at lower plant populations. The varieties TGx1448-2E and TGx1904-6F had higher IPAR than TGx1835-10E at both locations. The TGx1835-10E variety is earlier in maturity than the other two varieties. It has lower canopy area and less branching habit, which means that it can intercept a lower amount of solar radiation than the late maturing varieties, which grow and close their canopies earlier. The LAI varied with year, population, and variety, and generally increased with increasing plant population. The magnitude of the differences among populations was more pronounced in 2010 at Samaru Zaria and 2009 at Samaru-Kataf

Table 1. Probability of *F* values for physiological and agronomic responses of soybean varieties to plant population at two locations in the Guinea savannas of Nigeria.

Effect	IPAR†	Leaf area index	No. of pods m^{-2}	No. of seeds m^{-2}	Grain yield	Fodder yield
Samaru Zaria (NGS)‡					kg ha^{-1}	
Year (Y)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Plant population (P)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Y × P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0093
Variety (V)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Y × V	0.0113	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
P × V	0.4467	0.1732	0.0094	0.2815	0.0069	0.2238
Y × P × V	0.069	<0.0001	<0.0001	0.0077	0.0374	0.0034
Samaru-Kataf (SGS)§						
Year (Y)	<0.0001	<0.0001	0.0022	0.0019	0.8424	<0.0001
Plant population (P)	0.011	0.0002	<0.0001	0.0092	0.0001	0.0004
Y × P	0.4303	0.334	<0.0001	0.0043	0.0063	0.1754
Variety (V)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Y × V	<0.0001	<0.0001	<0.0001	<0.0001	0.0007	<0.0001
P × V	0.158	0.001	<0.0001	0.0002	0.4462	0.0777
Y × P × V	0.4169	<0.0001	<0.0001	<0.0001	0.0055	0.0155

† PAR, photosynthetically active radiation.

‡ NGS, northern Guinea savannah.

§ SGS, southern Guinea savannah.

Table 2. Effect of plant population and variety on percentage of intercepted photosynthetically active radiation (IPAR) in soybean at two locations in the Guinea savannas of Nigeria.

Effect	Samaru Zaria (NGS)†	Samaru-Kataf (SGS)‡
Population (plants ha^{-1})		
266,700	60c§	61b
333,300	66b	65b
533,300	72b	66b
666,700	78a	76a
LSD(0.5)	5.8	8.0
Variety		
TGx1835-10E	56b§	47b
TGx1904-6F	76a	75a
TGx1448-2E	75a	80a
LSD(0.5)	5.1	5.0

† NGS, northern Guinea savannah.

‡ SGS, southern Guinea savannah.

§ For plant population or variety, means followed by the same letter in a column are not significantly different according to LSD ($P \leq 0.05$).

(Table 3). The TGx1835-10E variety had lower LAI in all years at both locations. As an early maturing variety, it produced less biomass and leaf senescence began earlier than the other two varieties. Increasing the population to 533,300 and 666,700 increased the LAI of this variety. This may lead to higher light interception for dry matter production. According to Egli (1988), maximum yield can be obtained only if the plant community produces enough leaf area to provide maximum interception of solar radiation during reproductive growth.

Number of pods m^{-2} varied with year, population, and variety at both locations. Number of pods m^{-2} increased with increase in plant population. The increases were higher in Samaru Zaria than in Samaru-Kataf (Table 4). In Samaru Zaria, increases in number of pod m^{-2} were only significant at a population of 533,300 and 666,700 plants ha^{-1}, except in 2010 when the increase was also significant at 333,333 plants ha^{-1}. In Samaru-Kataf, significant increases in number of pods m^{-2} were only recorded at a population of 666,667 plants ha^{-1} in 2009, and at a population of 533,300 and 666,700 plants ha^{-1} in 2011. Number of pods m^{-2} did not significantly increase at high population levels in 2010, probably due to the lower amount of rainfall during this year. In Samaru Zaria, increases in the number of pods m^{-2} with increasing plant populations were higher for TGx1448-2E and TGx1904-6F than for TGx1835-10E in all the years. For all the varieties, the increases were significantly higher at plant populations of 533,300 and 666,700 plants ha^{-1}. The TGx1904-6F variety produced the highest number of pod ha^{-1} in all 3 yr. In Samaru-Kataf, TGx1448-2E and TGx1904-6F generally produced higher number of pods m^{-2} than TGx1835-10E. In 2009, TGx1835-10E produced number of pods that were similar to those produced by the other varieties when grown at lower plant populations of 266,700 and 333,300 plants ha^{-1}. Differences among the varieties were not significant at higher plant populations except at 666,700 plants ha^{-1}, when TGx1904-6F produced the highest number of pods m^{-2}. In 2010, there was no consistent response in terms of pod formation of all the varieties to changes in population. This may be due to insufficient moisture, because rainfall in this year was less than in the other years. The late or medium maturing varieties, however, produced significantly more pods than the early-maturing TGx1835-10E. In 2011, the number of pods m^{-2} at 666,700 plants ha^{-1} were almost double that produced at a plant population of 266,700 plant ha^{-1}. The TGx1448-2E and TGx1904-6F varieties produced a number of pods that were not significantly different from each other but produced significantly more pods than TGx1835-10E.

In Samaru Zaria, the response of the number of seeds m^{-2} of soybean varieties to population varied with year (Table 5). Averaged across the soybean varieties, the number of seed produced m^{-2} increased by 4.1% at 333,300, 31% at 533,300, and 43% at 666.700 plants ha^{-1} when compared with the 266,700 population ha^{-1} in 2009 at Samaru Zaria. In 2010, the increases were 59, 96, and 44% for 333,300, 533,300, and 666,700 plants ha^{-1}, respectively. The increases were smaller in 2011 (17, 26, and 26% for 333,300, 533,300, and 666,700 plants ha^{-1}, respectively) because the number of seeds produced was generally lower than the other years. In 2009 and 2011, the medium and late maturing varieties (TGx1904-6F and TGx1448-2E) produced the highest number of seeds m^{-2}. The magnitude of the differences between these two varieties and TGx1835-10E was higher in 2009 than in 2011. In 2010, TGx1448-2E produced the least number of seeds m^{-2} at all plant populations. The TGx1448-2E variety takes longer to flower and mature than the other two varieties. The poor rainfall distribution in 2010 may have affected its performance. In Samaru-Kataf, response of soybean to plant population in terms of number of seed m^{-2} was not consistent across years (Table 5). In 2009 increases in seed number only occurred at plant populations of 533,300 and 666,700 plant ha^{-1}. Response of soybean to plant population was not consistent in 2010. In 2011, there were 23, 51, and 83% increases in number of seeds m^{-2} at plant populations of 333,300, 533,300, and 666,700 plants ha^{-1}, respectively, relative to that at the 266,700 plants ha^{-1} population. The response of varieties to plant population changed with year. The TGx1904-6F variety produced the highest numbers of seeds m^{-2} in 2009 and 2011. In 2010, TGx1448-2E produced the highest number of seeds m^{-2} because of significant increases in the number of seeds produced at 333,300 and 533,300 plants ha^{-1}.

In Samaru Zaria, soybean grain yield increased with increase in plant population (Table 6). The increase in grain yield was dependent on soybean variety and year. In 2009, increases in grain yield were only significant at plant populations of 533,300 and 666,700 plants ha^{-1}. These increases represented 28 and 47% for populations of 533,300 and 666,700 plants ha^{-1}, respectively, compared with the lowest population. In 2010 and 2011, significant increases were recorded at populations of 333,300 plants ha^{-1} (22% in 2010 and 33% in 2011), 533,300 plants ha^{-1} (42% in 2010 and 56% in 2011), and 666,700 plants ha^{-1} (62% in 2010 and 100% in 2011). This corroborates the findings of Ball et al. (2000), which suggested that higher plant population consistently produced higher seed yields in Arkansas, USA under a short-season production system using indeterminate early maturing varieties. In 2009 and 2011, the increases were higher for the medium/late maturing TGx1448-2E and TGx1904-6F than TGx1835-10E. The TGx1835-10E variety produced higher grain yield than the other two varieties in 2010 due to the terminal drought that occurred toward the end of the growing season (Fig. 1). The rains stopped early in 2010, which may have affected the performance of the two medium/late maturing varieties. The early maturing variety had already completed pod-filling stage; hence, the low rainfall did not affect yield significantly. In Samaru-Kataf, there were consistent increases in soybean grain yield with increasing plant population in 2009 and 2011 (Table 6). Except for TGx1904-6F, the effect of

Table 3. Interactive effects of year, variety, and plant population on leaf area index in soybean at two locations in the Guinea savannas of Nigeria.

	2009					2010					2011				
						Population, plants ha^{-1}									
Variety	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean
Samaru Zaria (NGS)†															
TGX1835-10E	1.52b‡	1.86b	1.45b	1.66b	1.62	0.71b	1.01b	3.83b	5.08b	2.66	1.97b	3.65b	3.21c	4.30c	3.28
TGX1904-6F	3.98a	4.59a	4.96a	5.17a	4.68	1.56a	3.70a	4.12b	5.74ab	3.78	4.21a	5.03a	6.37a	8.00a	5.90
TGX1448-2E	4.59a	5.05a	5.24a	5.86a	5.19	1.75a	3.02a	5.16a	6.02a	3.99	4.12a	4.52a	5.25b	6.22b	5.03
Mean	3.36	3.83	3.88	4.23		1.34	2.58	4.37	5.62		3.44	4.4	4.94	6.17	
LSD P	0.294														
LSD V	0.204														
LSD(0.5) Y × P	0.509														
LSD(0.5) Y × V	0.353														
LSD(0.5) Y × P × V	0.705														
Samaru-Kataf (SGS)§															
TGX1835-10E	0.64b§	1.18b	0.75b	1.12b	0.92	1.27c	1.46c	1.86b	1.95c	1.63	0.16b	0.66b	1.37b	2.14b	1.08
TGX1904-6F	3.13a	4.17a	4.46a	5.05a	4.20	2.85b	2.88b	2.22a	5.20a	3.29	1.77a	2.03a	2.26a	3.00a	2.27
TGX1448-2E	2.73a	3.69a	4.88a	5.10a	4.10	5.24a	5.04a	4.80a	4.18b	4.82	1.48a	2.04a	1.53b	2.53ab	1.90
Mean	2.17	3.02	3.36	3.76		3.12	3.13	2.96	3.77		1.14	1.58	1.72	2.56	
LSD P	0.445														
LSD V	0.190														
LSD(0.5) Y × P	0.720ns¶														
LSD(0.5) Y × V	0.301														
LSD(0.5) Y × P × V	0.601														

† NGS, northern Guinea savannah.

‡ Within each location and for each column, means followed by the same letter are not significantly different according to LSD ($P \leq 0.05$).

§ SGS, southern Guinea savannah.

¶ ns, not significant at 0.05 probability level.

Table 4. Interactive effects of year, variety, and plant population on number of pods in soybean at two locations in the Guinea savannas of Nigeria.

Variety	2009					2010					2011				
	Population, plants ha^{-1}														
	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean
	no. m^{-2}														
Samaru Zaria (NGS)†															
TGX1835-10E	628.7c‡	671.8b	1086.9a	1252.4b	909.9	537.6c	898.7c	1126.2c	1322.2c	971.2	560.9b	694.4b	781.8b	839.6c	719.2
TGX1904-6F	1076.2a	968.2a	1033.3a	1338.0a	1103.9	991.1a	1220.2b	1548.7a	1882.9a	1410.7	848.9a	973.6a	1358a	1485.3a	1166.4
TGX1448-2E	933.1b	884.2a	1148.2a	1123.8b	1022.3	819.3b	1365.1a	1369.3b	1618.0b	1292.9	698.2b	773.3b	908.4b	1148.4b	882.1
Mean	879.3	841.4	1089.5	1238.1		782.7	1161.3	1348.1	1607.7		702.7	813.8	1016.1	1157.8	
LSD P	46.53														
LSD V	40.15														
LSD(0.5) Y × P	80.6														
LSD(0.5) Y × V	69.54														
LSD(0.5) Y × P × V	139.1														
Samaru-Kataf (SGS)§															
TGX1835-10E	509.3b§	444.4b	792.7b	906.4ab	663.2	583.1c	621.8b	578.0b	469.3b	563.1	358.7b	464.4b	641.6c	734.4c	549.8
TGX1904-6F	788.4a	753.3a	836.0ab	1046.7a	856.1	819.6b	919.8a	1115.7a	1059.5a	978.6	803.8a	896.4a	1421.3a	1898.2a	1254.9
TGX1448-2E	874.0a	805.6a	965.8a	776.0b	855.3	1243.8a	1068.6a	1014.9a	949.2a	1069.1	649.8a	796.9a	865.8b	1460.4b	943.2
Mean	723.9	667.8	864.8	909.7		882.2	870.0	902.9	826.0		604.1d	719.3c	976.2b	1364.4a	
LSD P	73.74														
LSD V	51.41														
LSD(0.5) Y × P	114.52														
LSD(0.5) Y × V	82.06														
LSD(0.5) Y × P × V	164.12														

† NGS, northern Guinea savannah.

‡ Within each location and for each column, means followed by the same letter are not significantly different according to LSD ($P \leq 0.05$).

§ SGS, southern Guinea savannah.

plant population on soybean grain yield was not consistent in 2010. In 2010, the grain yield of TGx1904-6F increased by 13, 29, and 28% when populations increased from 266,700 to 333,300, 533,300, and 666,700 plants ha^{-1}, respectively, suggesting that the optimum population was 533,300 plants ha^{-1}. In 2009, TGx1448-2E and TGx1904-6F produced similar grain yields and both were higher than that for TGx1835-10E at all plant populations. In 2011, TGx1904-6F produced the highest grain yield. Each of the varieities produced over twice the grain yield at a plant population of 666,700 ha^{-1} than that produced at a plant population of 266,700 plants ha^{-1}. At both locations, optimum plant population occurred between 533,300 to 666,700 plants ha^{-1} with year-to-year variations. The increases may be due to consistent increases in number of pods plant^{-1} and number of seeds plant^{-1}. In contrast to Ball et al. (2001) and Carpenter and Board (1997), there was no compensation for number of pods plant^{-1} and grain yield at lower plant population. Our results suggest that the soybean growing environment in northern Nigeria is suitable enough to support high soybean populations. The northern Guinea savanna location produced more yield at higher plant populations than the southern Guinea savanna. In contrast to the results of De Bruin and Pedersen (2008b), where the optimum plant population for soybean was lowest when growing conditions were favorable, our data suggested that the optimum population was higher under a favorable environment than when grown under relatively lower rainfall conditions. Optimum grain yield was attained at plant populations between 533,300 and 666,700 in 2009 and 2011. However, when rainfall was poor in 2010, grain yield increases were minimal at plant populations above 333,300. There are two explanations for this. In dry conditions in 2010, there may have been competition for water, which led to low grain yield, indicating that perhaps seed size was decreased in 2010. This is similar to findings of Madanzi et al. (2012) in Zimbabwe, who reported that low availability of water was a limiting factor to soybean grain yield at high plant populations beyond 200,000 plants ha^{-1}. Norsworthy and Frederick (2002) noted that rainfall was more important than seeding rate or variety. Our results support that of Devlin et al. (1995), which showed that drought stress during the reproductive growth stage reduced optimum plant populations. They reported that during drought stress, high plant populations exhausted soil water sooner than low plant populations resulting in a greater relative yield loss. Consequently, optimal plant populations under drought conditions was achieved with a seeding rate of only 129,112 vs. 573,040 seed ha^{-1} for plants that received adequate water.

Plant biomass increased with increasing plant populations in all years in Samaru Zaria (Table 7). The magnitude of the increases varied with years. In 2009, yield increases were 24, 37, and 69% for populations of 333,300, 533,300, and 666,700 plants ha^{-1}, respectively, compared with the 266,700 plants ha^{-1}. In 2010, fodder yield increased 18, 46, and 51% when plant populations were increased from 266,700 ha^{-1} to 333,300, 533,300, and 666,700 plants ha^{-1}, respectively. Although fodder yield was generally higher in 2009 than the other years, the highest fodder yield response occurred in 2011 when yield for 666,700 plants ha^{-1} increased by 74% compared with that for 266,700 plants ha^{-1}. In 2009, TGx1904-6F produced the highest fodder yield of 7.5 Mg ha^{-1} when averaged over plant populations. In 2010 and 2011, differences between TGx1448-2E and TGx1904-6F were not significant at all population levels. The TGx1835-10E variety produced the least fodder yield except in 2011, when it produced mean fodder yield that was not significantly different from that produced by TGx1904-6F. The lower fodder yield of TGx1835-10E may be due to its earliness in maturity, which does not allow high biomass production. Fodder yield in Samaru-Kataf was dependent on year and variety. Fodder yield was generally higher in 2010 than in the other years because the plants produced less grain in 2010 (Table 7). Fodder yield increased with increases in population in 2009 and 2011. The increases were, however, only significant at populations of 533,300 and 666,700 plants ha^{-1}. The TGx1835-10E variety produced the least fodder at all population levels in all the years. Except in 2010 when TGx1904-6F produced lower fodder yield at a population of 266,700 plants ha^{-1} and higher fodder yield at 666,700 plants ha^{-1}, fodder yield did not differ between TGx1448-2E and TGx1904-6F in all years.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The widely used plant population of 266,700 plants ha^{-1} was not confirmed to be optimum for soybean production in the Guinea savannas of Nigeria.
2. Response of soybean varieties to plant population varied with year. In a year of below normal rainfall (as in 2010) soybean yield was lower at high plant populations.
3. The optimum plant population in years of above or normal rainfall appeared to be between 533,300 and 666,700, suggesting that soybean yields in the Guinea savanna of northern Nigeria can be increased using plant population higher than the current recommendation.
4. The varieties TGx1448-2E and TGx1904-6F intercepted higher proportion of IPAR, had higher LAI, and produced greater number of pods m^{-2}, seeds m^{-2}, grain yield, and fodder than TGx1835-10E at both locations in years of normal or above-normal rainfall.

Table 5. Interactive effects of year, variety, and plant population on number of seeds in soybean at two locations in the Guinea savannas of Nigeria.

	2009					2010					2011				
	Population, plants ha^{-1}														
Variety	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean
	no. m^{-2}														
Samaru Zaria (NGS)†															
TGX1835-10E	1154b‡	1263.1b	1771.1b	1890.4b	1519.7	1158.0b	1999.8a	2680.7a	2863.8b	2175.6	1056.9b	1140.7b	1170.0c	1356.4c	1181
TGX1904-6F	1774.9a	1911.6a	2118.0a	2467.8a	2068.1	1476.2a	2040.4a	2634.7a	3091.1a	2310.6	1306.9ab	1633.8a	1855.3a	2124.7a	1730.2
TGX1448-2E	1742.9a	1693.6a	2257.3a	2368.4a	2015.6	1052.7b	1822.0a	1904.2b	2503.6c	1820.6	1115.3b	1280.0b	1436.7b	1618.4b	1362.6
Mean	1557.3	1622.7	2048.8	2242.2		1229.0	1954.1	2406.5	2819.5		1159.7	1351.5	1487.3	1699.9	
LSD P	82.89														
LSD V	71.79														
LSD(0.5) Y × P	143.58														
LSD(0.5) Y × V	124.34														
LSD(0.5) Y × P × V	248.68														
Samaru-Kataf (SGS)§															
TGX1835-10E	728.9b§	932.4b	1478.2b	1621.3b	1190.2	1187.7c	1319.6c	1055.8c	943.3c	1126.6	704.0b	851.3b	980.2c	1124.2c	914.9
TGX1904-6F	1612a	1829.1a	1770.7a	1840.4a	1763.1	1590.7b	1567.6b	1503.8b	1643.3a	1576.3	1095.3a	1389.1a	1680.2a	2158.9a	1580.9
TGX1448-2E	1710.2a	930.9b	1726.9a	1463.6b	1457.9	1861.0a	2205.2a	2154.9a	1416.7b	1909.4	875.3b	1055.6b	1381.8b	1602.2b	1228.7
Mean	1350.4	1230.8	1658.6	1641.8		1546.5	1697.4	1571.5	1334.4		891.6	1098.7	1347.4	1628.4	
LSD P	168.06														
LSD V	68.09														
LSD(0.5) Y × P	272.6														
LSD(0.5) Y × V	107.8														
LSD(0.5) Y × P × V	215.6														

† NGS, northern Guinea savannah.

‡ Within each location and for each column, means followed by the same letter are not significantly different according to LSD ($P \le 0.05$).

§ SGS, southern Guinea savannah.

Table 6. Interactive effects of year, variety, and plant population on grain yield in soybean at two locations in the Guinea savannas of Nigeria

	2009					2010					2011				
	Population, plants ha^{-1}														
Variety	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean
	kg ha^{-1}														
Samaru Zaria (NGS)†															
TGX1835-10E	1046.2c‡	1010.3b	1616.7b	1723.8c	1349.2	1905.3a	2563.3a	2585.3a	3146.3a	2550	724.1c	1105.6b	1691.2c	2745.9b	1566.7
TGX1904-6F	3289.9a	2615.1a	3780.1a	4436.1a	3530.3	1846.4a	1701.0b	2070.0b	2650.3b	2066.9	3006.7a	3613.5a	4072.8a	4799.4a	3873.1
TGX1448-2E	2501.8b	2739.4a	3355.9a	3924.1b	3130.3	1343.6b	1939.6b	2570.7a	2462.3b	2079.1	2253.2b	3261.7a	3594.8b	4467.7a	3394.3
Mean	2279.3	2121.6	2917.5	3361.3		1698.4	2068	2408.7	2753.0		1994.6	2660.3	3119.6	4004.3	
LSD P	142.73														
LSD V	123.60														
LSD(0.5) Y × P	247.2														
LSD(0.5) Y × V	214.08														
LSD(0.5) Y × P × V	428.18														
Samaru-Kataf (SGS)§															
TGX1835-10E	733.0b§	1142.9b	1478.2b	1883.1b	1309.3	1359.4c	1373.3b	1348.3b	967.4b	1262.1	788.5c	1208.3c	1560.6b	2078.0c	1408.9
TGX1904-6F	2049.0a	1860.9a	2251.7a	2376.8a	2134.6	1823.6b	2064.0a	2365.1a	2337.3a	2147.5	1625.1a	2177.4a	2495.3a	3276.5a	2393.6
TGX1448-2E	1978.8a	1725.5a	2357.9a	2548.0a	2152.5	2534.4a	2298.4a	2222.8a	2106.5a	2290.5	1149.8b	1808.7b	2311.3a	2671.8b	1985.4
Mean	1586.9	1576.4	2029.3	2269.3		1905.8	1911.9	1978.7	1803.7		1187.8	1731.5	2122.4	2675.5	
LSD P	267.08														
LSD V	103.41														
LSD(0.5) Y × P	434.44														
LSD(0.5) Y × V	163.68														
LSD(0.5) Y × P × V	327.36														

† NGS, northern Guinea savannah.

‡ Within each location and for each column, means followed by the same letter are not significantly different according to LSD ($P \leq 0.05$).

§ SGS, southern Guinea savannah.

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Table 7. Interactive effects of year, variety, and plant population on fodder yield in soybean at two locations in the Guinea savannas of Nigeria.

	2009					2010					2011				
	Population, plants ha^{-1}														
Variety	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean	266,700	333,300	533,300	666,700	Mean
	kg ha^{-1}														
Samaru Zaria (NGS)†															
TGX1835-10E	1238.7c‡	1577.4c	2116.6c	2724.1c	1914.2	3037.7a	3047.7b	4137.4b	5003.5a	3806.6	1609.2b	2269.7b	3397.7a	4153.9b	2857.6
TGX1904-6F	5999.3a	7328.2a	7561.3a	9168.7a	7514.4	3806.0a	4056.4a	5045.8a	5049.2a	4489.4	2748.6a	2951.9a	2636.1b	4371.7a	3177.1
TGX1448-2E	4608.0b	5770.9b	6501.5b	8149.3b	6257.4	3300.9a	4885.8a	5671.0a	5230.4a	4772.0	3118.4a	3335.2a	3926.1a	4460.7a	3710.1
Mean	3948.7	4892.2	5393.1	6680.7		3381.5	3996.6	4951.4	5094.4		2492.1	2852.3	3319.9	4328.8	
LSD P	280.74														
LSD V	243.14														
LSD(0.5) Y × P	486.26														
LSD(0.5) Y × V	421.12														
LSD(0.5) Y × P × V	842.24														
Samaru-Kataf (SGS)§															
TGX1835-10E	1089.6b§	1511.9b	2256.4b	2581.4b	1859.8	2916.5c	2957.6b	2894.1b	2601.8c	2842.5	1575.5ab	1547.4b	2458.3b	2798.8b	2095.0
TGX1904-6F	2530.8a	2300.0a	3041.5a	3313.5a	2796.4	3729.6b	4603.2a	5178.1a	5368.1a	4719.7	2301a	2922.9a	3297.6a	4045.3a	3141.7
TGX1448-2E	2658.1a	2563.9a	3430.3a	3382.6a	3008.7	5553.7a	4703.0a	5003.4a	4416.8b	4919.3	1908.7a	2146.9b	3350.6a	3652.9a	2764.8
Mean	2092.8	2125.3	2909.4	3092.5		4066.6	4088	4358.5	4128.9		1928.4	2205.8	3035.5	3499	
LSD P	415.04														
LSD V	207.84														
LSD(0.5) Y × P	666.54ns¶														
LSD(0.5) Y × V	325.06														
LSD(0.5) Y × P × V	650.12														

† NGS, northern Guinea savannah.

‡ Within each location and for each column, means followed by the same letter are not significantly different according to LSD ($P \le 0.05$).

§ SGS, southern Guinea savannah.

¶ ns, not significant at 0.05 probability level.