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Response of eight sorghum varieties to plant density and nitrogen fertilization in the Sudano-Sahelian zone in Mali

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This work was conducted to study the performance of eight sorghum varieties that contrasted with intensified practices in the Sudano-Sahelian zone of Mali. Two experiments were carried out in 2018 and 2019 rainy seasons at Sotuba Agricultural Research Station in Mali. The experimental design used was a Split-split-plot with three replications and three factors including two plant densities (D1: 26666 plants ha^{-1} and D2: 53333 plants ha^{-1}) as the main plot, three nitrogen levels (0, 41 and 82 kg N ha^{-1}) as the subplot and varieties as the sub-subplot. Measurements focused on growth and physiological parameters, grain yield and yield components. The results showed that sorghum grain yield was positively correlated with straw yield, leaf area index, grain number per panicle, panicle number per m^2, panicle weight per m^2 in N0D1 (0 kg N ha^{-1} and 26666 plants ha^{-1}) and N2D2 (178 kg N ha^{-1} and 53 333 plants ha^{-1}). Furthermore, straw yield was positively correlated with the leaf area index and panicle weight m-² in N0D1 and in N2D2. Analysis of variance showed that plant density, nitrogen and variety effect on grain and straw yields were significant. The interaction density x nitrogen x variety effect was also significant on grain and straw yields. Grain and straw yields were high in the N2D2 treatment for eight varieties compared to the N0D1 treatment. GRINKAN, C2_075-15 and C2_007-03 varieties had the highest grain and straw yields in N0D1. These caudatum-type varieties could be recommended in less intensive sorghum production areas in Mali. The FADDA variety produced high grain and straw yields in N2D2. Guinea-type hybrid FADDA may be recommended for grain and straw production in intensive sorghum production areas in Mali.

Key words: Mali, intensification, varieties, Nitrogen, planting density, yields.

INTRODUCTION

Sorghum is one of the staple cereals grown in the semi-arid and arid regions of Africa and Asia (Srinivas et al., 2009; Borrell et al., 2014). It ranks fifth in the world in terms of production and growing area and the fourth most cultivated cereal in Mali during the raining season for human consumption and animal feeding. Despite its importance, sorghum yield remains low with less than one ton per hectare at national scale (Trouche et al., 2001). This low yield is mainly attributed to spatial and temporal variability in rainfall, poor soil fertility and extensive traditional agronomic management practices (Trouche et al., 2001; Leibman et al., 2014). Until now, to meet the food demand of the growing population, increase in production has been mainly achieved by expanding the areas dedicated to crop cultivation (Hanak-Freud, 2000). This strategy is limited by urbanization and the saturation of the rural space leading the farmers to use intensification method (Brocke et al., 2002; Xie et al., 2019). In addition, sorghum cultivation is highly competitive by potentially productive maize in areas of intensification in Mali (Bazile et al., 2008; Vaksmann et al., 2008). Presently, it is well documented that grain yield depends both on crop genetic potential and agronomic practices such as plant density and mineral fertilization (Moosavi et al., 2013; Kondombo et al., 2017). Numerous studies have shown the importance of plant density and nitrogen fertilization on sorghum production (Bayu et al., 2005; Akmal et al., 2010; Arunakumari and Rekha, 2016). In addition, previous studies reported that the optimum plant density depends on each crop (Biswas and Ahmed, 2014), beyond which the competition between plants for light, water and nutrients becomes important and can lead to decreased crop yields (Berenguer and Faci, 2001; Çalifikan et al., 2007; Li et al., 2016). Nitrogen is also one of the most important nutrients which must be used in an optimal quantity depending on plant density as its lack or excess can reduce crop productions (Fischera and Wilsonb, 1975; Ferraris and Charles, 1986; Tajul et al., 2013; Sher et al., 2016).

Recently in Mali, to increase sorghum production, mineral fertilization studies were experimented and diffused on sorghum varieties (Kouyate and Wendt, 1991; Zougmoré et al., 2003; Coulibaly et al., 2019). However, plant density of 25.000 hills/ha and the doses of 100 kg ha^{-1} diammonium phosphate (DAP) at sowing and 50 kg ha^{-1} urea before the panicle initiation were recommended for sorghum cultivation (Kouyate and Wendt, 1991; Coulibaly et al., 2019). These agronomic practices advised in the growing areas were disseminated separately either on local sorghum or on improved sorghum. Nowadays, little research has been done to understand the performance of newly improved sorghum varieties to respond to plant density and nitrogen fertilization to intensify grain and straw production. A better knowledge on the effect of these techniques on sorghum productivity (grain and straw) should contribute to a better understanding of the constraints related to sorghum intensification in the Sahel. The objective of this study was to identify sorghum varieties that respond to plant density and nitrogen fertilization, and to determine agro-morphological and physiological traits involved in the variation in plant density and nitrogen fertilization.

MATERIALS AND METHODS

Experimental site and growing conditions

Two field trials were conducted in the rainy seasons of 2018 and 2019 at the Sotuba Agricultural Research Station in Mali (12°39' N and 07°56' W). The climate of this area is Sudano-Sahelian type with an average annual rainfall of 866 mm on the period 1981-2010. The cumulative annual rainfall recorded in 2018 was 840 mm against 1158 mm in 2019 (Figure 1). The average annual temperatures during the 2018 and 2019 experiments were 27 and 28°C, respectively. In 2018, trial was conducted on sandy-silty soil (96.84%) with low clay content (3.85%), water pH (5.75), organic matter (0.37%), nitrogen (0.12%), assimilable phosphorus (10.77 ppm) and exchangeable potassium (0.13 meq/g). However, in 2019, the experimentation was carried out on sandy-silty soil (80%) with a clay content (20%), water pH (6.20), organic matter (1.46%), nitrogen (0.25%), assimilable phosphorus (14 ppm) and exchangeable potassium (0.40 meq/g). Sampling of the experimental soils was done at a 0-40 cm depth.

Plant materials

Eight contrasting sorghum varieties for different agro-morphological and physiological traits were assessed: hybrid varieties FADDA and PABLO (hybrid varieties) and open pollinated varieties SOUMBA, GRINKAN, WILIBALI (C2_007-03), WASSALEN (C2_075-15) and TINSAMBA (A12-79). The local variety TIEBILE (CSM335) was the control in this study (Table 1). These varieties represent the diversity of improved sorghum grown in Mali.

Experimental design and crop management

A split-split-plot design was used to study three factors including two plant densities (D1: 26666 plants ha^{-1} and D2: 53333 plants ha^{-1}) as the main plot, three nitrogen levels (0, 41 and 82 kg ha^{-1}) as the subplot and varieties as the sub-subplot with three replications. The dose of nitrogen recommended in Mali for the sorghum cultivation is 41 kg ha^{-1} (Kante et al., 2017). A total of 144 treatments were used. The area for each elementary plot was 18 m^2 (6 lines 4.5 m long and 4 m wide). The seeding spacing was 0.75 m x 0.5 m for the low density (D1) and 0.75 m x 0.25 m for the high density (D2). The soil was ploughed to a depth of about 30 cm. Sowing was done on June 18th, 2018 and on July 5th, 2019 after a good rainfall (25 mm) at a rate of 5 to 6 seeds per hill. Around 15 days after emergence, the plots were thinned to one plant per hole in wet condition. Nitrogen was applied in the form of urea in two fractions, three weeks after thinning (50%) of the plants and before

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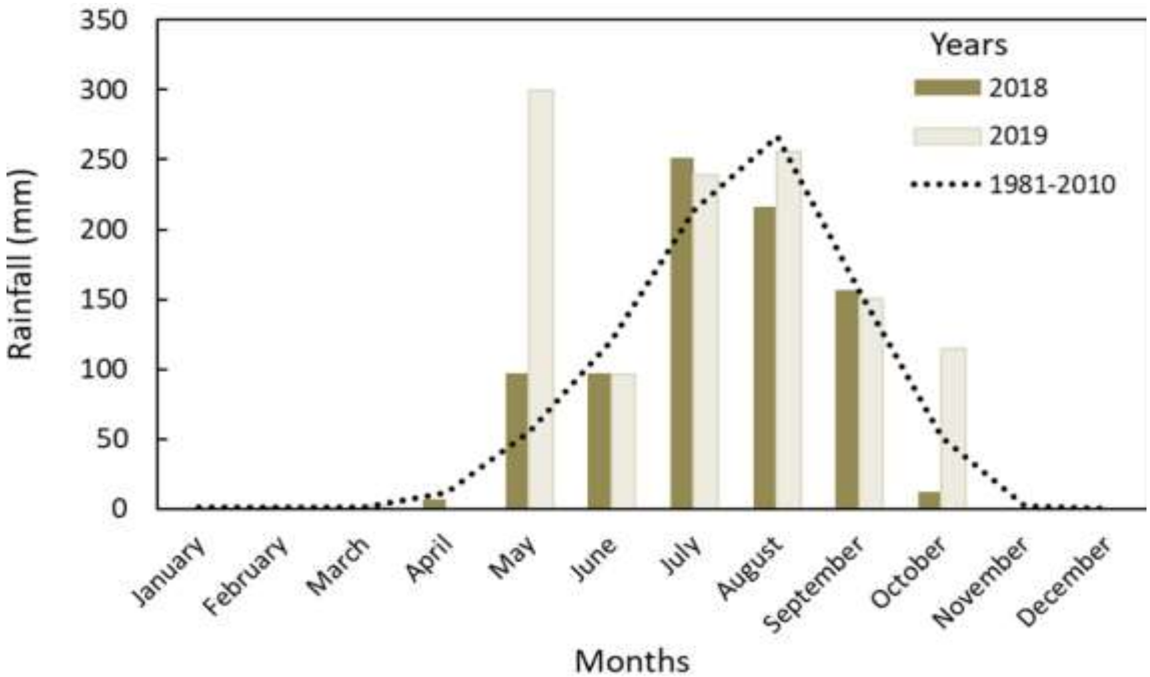

Figure 1. Monthly rainfall for 2018, 2019 and the last 30 years (1981-2010) recorded in Sotuba of January to December.

Table 1. Characteristics of eight sorghum varieties used in the 2018 and 2019 experiments.

Variety	Origin	Race	Cycle duration (days)	Plant height (cm)	Grain yield (t ha^{-1})	Isohyete (mm)
FADDA	Mali	Guinea (hybride)	117	300	4	700-1000
PABLO	Mali	Guinea (hybride)	115	400	4	700-1000
GRINKAN	Mali	Caudatum	125	200	2.8	800-1000
SOUMBA	Mali	Caudatum	110	240	2.8	600-800
TIEBILE	Mali	Guinea	125	360	2.5	800-1000
C2_007-03	Mali	Guinea-Caudatum	130	210	3.3	800-1000
C2_075-15	Mali	Guinea-Caudatum	130	170	3.3	800-1000
A12-79	Mali	Durra-Caudatum	135	175	4	800-1000

the panicle initiation (50%). Basal application of Phosphorus (46 kg P_2O_5) was homogeneously made in all plots before sowing as “phosphate naturel de Tilemsi” (PNT) granulated (31% P_2O_5). Two manual weeding were carried out in each experiment and crop ridging was performed after the second nitrogen application. Breakouts were realized between blocks and between replications to reduce nitrogen exchange. All plots were treated with EMACOT 050 WG insecticide in the vegetative phase of the crops according to the infestation level to control the attacks of legionary caterpillars (Spodoptera exempta).

Measurements and sampling

The phyllochron was calculated according to the ratio of number of days necessary for the appearance of the flag leaf to the total number of leaves that appeared on the main stem. Its measurement was carried out on three plants randomly selected from each elemental plot.

Physiological measurements were realized at flowering and carried on the leaf area index and chlorophyll estimation. The leaf area index was estimated with a Sunscan Septometer (Delta-T Device Ltd) equipped with an external BF5 sensor on plots (1 m^2) delimited in each elementary plot. The chlorophyll estimation was done with a SPAD-502 device. It was carried on the 3rd ligulated leaf of the main stalk from the top of the plant and was performed on the three plants used for the phyllochron determination. An area of 2.25 m² was used for plant height measurements, yield components, straw biomass and grain yield at physiological maturity. The seedlings of 6 hills for the low density and 12 hills for the high density were collected. Plant height was measured with a ruler and the panicule number per m² was assessed by manual counting. After harvesting (panicle and dry straw) and sun drying for one month, panicle weight per m² and straw yield were determined.

The dried panicles were threshed to determine grain yield. The 1000-grains weight was obtained by counting with an electric counter (NUMIGRAL) and the grain numbers per panicle was also calculated according to the ratio of average panicle weight to grain weight.

Data statistical analysis

The combined variance analysis of the two trials was performed with the "agricolae" package for the environment (Venables, Smith and the R Core Team, 2019) according to the split-split-plot model developed by Carmer et al. (1989). Shapiro-Wilk normality and Bartlett homogeneity tests were performed to identify and exclude aberrant data induced by soil heterogeneity for different measured variables. The Tukey test (smallest significant difference, LSD) at the 5% threshold was used to compare the means of the studied factors. Pearson correlation analyses were performed with the "Hmisc" package and the principal component analyses (PCA-biplot) were performed with the "FactoMineR" and "factoextra" packages in the same R software.

RESULTS

Grain yield and straw yield

The analysis of variance showed significant effects of the year, density, nitrogen dosage and variety on grain and straw yields. The interaction effects between year x density and year x nitrogen were also significant on grain and straw yields; and the year x variety interaction was significant for straw yield (Table 2). The interaction effects between nitrogen x variety and density x nitrogen x variety were likewise significant on grain yield and straw yield.

The highest grain yield was recorded in 2019 (3644 kg ha^{-1}) compared to 2018 (3322 kg ha^{-1}). Grain yield increased from 2975 kg ha^{-1} in D1 (26 666 plants ha$^{-1)}$ to 4013 kg ha^{-1} in D2 (53 333 plants ha^{-1}). Nitrogen application increased grain yield from 2918 kg ha^{-1} in N0 (0 kg Nha^{-1}) to 3935 kg ha-1 in N2 (178 kg Nha^{-1}). Straw yield was also higher in 2019 (18054 kg ha^{-1}) than 2018 (10510 kg ha^{-1}). It increased from 12785 kg ha^{-1} in D1 to 15995 kg ha^{-1} in D2; and from 12413 kg ha^{-1} in N0 to 16151 kg ha^{-1} in N2 (Table 2). Under different plant density and nitrogen combinations, high grain and straw yields were observed in the N2D2 treatment (178 kg N ha^{-1} and 53 333 plants ha^{-1}) for all varieties than in the N0D1 treatment (0 kg N ha^{-1} and 26 666 plants ha^{-1}). In N2D2, FADDA variety performed with a grain yield of 6241 kg ha^{-1}. It is followed by A12-79 (5342 kg ha^{-1}) while SOUMBA variety produced the lowest grain yield of 3193 kg ha-1 in N2D2 (Figure 2B). The same remark was made for straw yield, where FADDA (23511 kg ha^{-1}) was the best performing variety in N2D2. The C2_075-15 variety had the lowest straw yield, 14370 kg ha^{-1} (Figure 2D). In N0D1 (0 KgN ha^{-1} and 26666 plants ha^{-1}), GRINKAN, C2_075-15, C2_007-03, TIEBILE and SOUMBA varieties produced the highest grain yield with an average of 2694 kg ha^{-1}. Variety A12-79 recorded the lowest grain yield of 1806 kg ha^{-1} (Figure 2A). For straw yield, GRINKAN was the best performing variety (14474 kg ha^{-1}) in N0D1 and FADDA, TIEBILE, A12-19 and PABLO varieties produced the lowest straw with an average of 9234 kg ha^{-1} (Figure 2C). These results indicate that the increase in grain and straw yields is related to the increase in plant density and nitrogen application.

Agronomical and physiological parameters

The analysis of variance showed significant effects of the year, density, nitrogen and variety on the measured parameters (Table 3). The density x variety and nitrogen x variety interactions effects were significant on panicle number m-², panicle weight m^{-2} and plant height. The interaction effect between nitrogen x variety was also significant on SPAD value.

The panicle number m-² increased significantly with the increasing in plant density and nitrogen application. FADDA and TIEBILE varieties obtained on average 6.81 panicle m^{-2} in D2 (53 333 plants ha^{-1}). In addition, FADDA variety produced 7.41 panicle m^{-2} in N2 (178 kg Nha^{-1}) compare to the other varieties. FADDA variety obtained a panicle weight m^{-2} of 675 g in D2 and 7.94 g in N2 than the other varieties. FADDA statistically had the same panicle weight m^{-2} as PABLO and A12-79 in D2. For 1000WG, PABLO and TIEBIELE varieties recorded on average 24 g and the A12-79 variety was the least performing. The D1 density produced 457 more grains per panicle than the D2 density. It varied from 2803 grains in N0 to 3165 grains in N1 (89 kg N ha^{-1}) (statistically equal to N2). A12-79 variety had significantly the highest grain per panicle (3475). For plant height, PABLO variety was the longest in D2 (437 cm). It varied from N0 (269 cm) to N1 (279 cm) (statistically identical to N2).

The leaf area index value was 2.33 and 2.99 respectively in D1 and D2. Nitrogen input increased the vegetation cover from 2.49 in N0 to 2.89 in N2. FADDA had significantly the highest leaf area index (2.99) and A19-79 obtained lower value of 2.27. PABLO and FADDA varieties performed with SPAD values of 49.9 and 49.7 respectively in N2. It was 44.77 in D1 and 43.45 in D2. Phyllochron ranged from 3.01 days in D1 to 3.20 days in D2. Nitrogen application shortened phyllochron from 0.20 days in N2 to 0.08 days in N1. FADDA and PABLO varieties recorded a short phyllochron with an average of 2.96 days than the C2_007-03 and TIEBILE varieties, which averaged 3.23 days.

Contribution of variables to grain and straw production in sorghum

To better understand the variable contributions to the increase in grain yield and straw yield, a correlation

Table 2. Analysis of variance of the factors year (Y), plant density (D), nitrogen (A) and their interactions on grain yield (GY) and straw yield (STY) in 2018 and 2019.

Treatment	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
Year		
2018	3322[b]	10510[b]
2019	3644[a]	18054[a]
Density (Plants ha^{-1})		
D26666 (D1)	2975[b]	12785[b]
D53333 (D2)	4013[a]	15995[a]
Nitrogen (Kg N ha^{-1})		
N0	2918[c]	12413[c]
N89 (N1)	3647[b]	14597[b]
N178 (N2)	3935[a]	16151[a]
Variety (V)		
A12-79	3338[bc]	13307[de]
C2_007-03	3575[b]	15453[b]
C2_075-15	3391[bc]	12228[e]
FADDA	4473[a]	17656[a]
GRINKAN	3358[bc]	14384[bcd]
PABLO	3578[b]	13784[cd]
SOUMBA	2958[c]	13528[de]
TIEBILE	3396[bc]	15050[bc]
Source of variation		
Year (Y)	***	***
Density (D)	***	***
Nitrogen (N)	***	***
Variety (V)	***	***
Y x D	*	*
Y x N	***	**
D x N	NS	NS
Y x V	NS	***
D x V	NS	NS
N x V	***	**
Y x D x N	NS	NS
Y x D x V	NS	NS
Y x N x V	NS	NS
D x N x V	**	*
Y x D x N x V	NS	NS

Values in the same column followed by different letters are significantly different at $p < 0.05$. *, **. *** Significantly different at 5, 1 and 0.1% respectively; NS, non-significant. D26666 (D1: 26666 plants ha^{-1}) and D53,333 (D2: 53333 plants ha^{-1}); N0 (0 kg N ha^{-1}), N89 (N1: 89 kg N ha^{-1}) and N178 (N2: 178 kg N ha^{-1}).

matrix was carried out on the average of N0D1 (Table 4) and N2D2 (Table 5) treatments. Grain yield was significantly and positively correlated with the leaf area index, grain number per panicle, panicle number per m^2, panicle weight per m^2 and straw yield in N0D1 and N2D2; and negatively correlated to phyllochron in N2D2. Straw yield was significantly and positively correlated to leaf area index, grain number per panicle, panicle number per m^2 and panicle weight per m^2 in N0D1 and N2D2. It was negatively correlated with plant height in N0D1 and

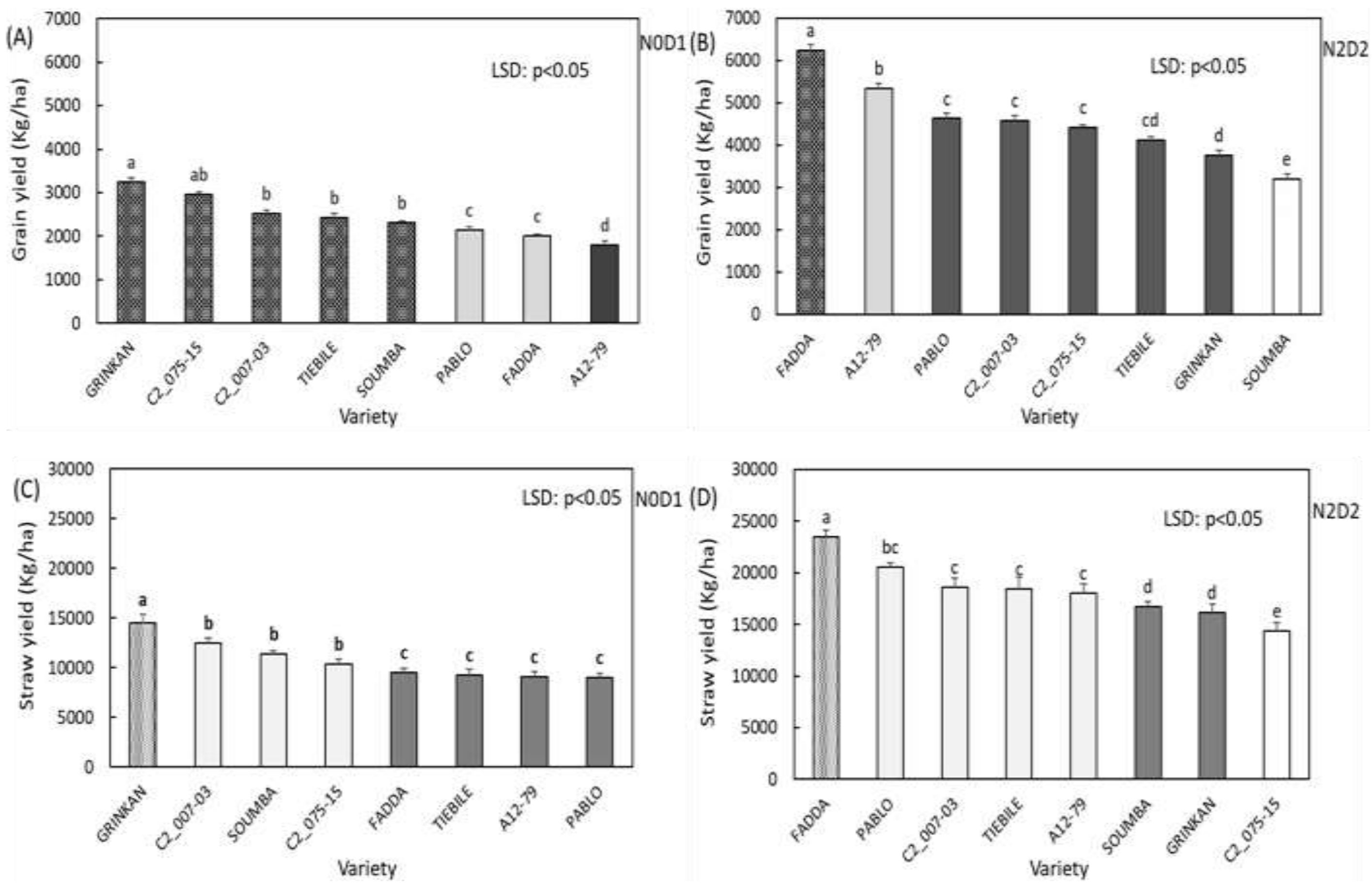

Figure 2. Grain yield (A) and (B); Straw yield (C) and (D) of eight sorghum varieties under different plant densities and nitrogen fertilization levels. N0D1 (0 kg N ha^{-1} and 26666 plants ha^{-1}), N2D2 (178 kg N ha^{-1} and 53333 plants ha^{-1}).

Table 3. Analysis of variance of the effects year, density, nitrogen variety and their interactions on the variables measured in 2018 and 2019.

Source of variation	panicle number per m^2	panicle weight per m^2	1000-Grain weight (g)	Grain number per panicle	Plant height (Cm)	Leaf area index	SPAD value	Phyllochron
Year (Y)	***	***	***	***	***	***	***	*
Density (D)	***	***	*	***	***	***	*	***
Nitrogen (N)	*	***	NS	*	***	**	***	***
Variety (V)	***	***	***	***	***	**	***	***
Y x D	*	NS	NS	NS	NS	NS	NS	NS
Y x N	*	***	NS	NS	NS	NS	NS	NS
D x N	NS	NS	NS	NS	NS	NS	NS	NS
Y x V	***	NS	***	NS	***	***	***	NS
D x V	**	*	NS	NS	***	NS	NS	NS
N x V	**	**	NS	NS	***	NS	*	NS
Y x D x N	NS	NS	NS	NS	NS	NS	NS	NS
Y x D x V	NS	NS	NS	NS	NS	NS	NS	NS
Y x N x V	NS	NS	NS	NS	NS	NS	NS	NS
D x N x V	NS	NS	NS	NS	NS	NS	NS	NS
Y x D x N x V	NS	NS	NS	NS	NS	NS	NS	NS

*, **. *** Significantly different at 5, 1 and 0.1% respectively; NS, non-significant.

Table 4. Correlation between agronomical traits and physiological parameters measured in N0D1.

Variable	Grain yield	Leaf area index	grain number per panicle	Plant height	Phyllochron	Panicle number per m^2	Panicle weight per m^2	SPAD value	Straw yield
Grain yield	1								
Leaf area index	0.84**								
Grain number/panicle	0.66**	0.24							
Plant height	-0.28	0.13	-0.76**						
Phyllochron	0.27	0.47*	-0.04	0.12					
Panicle number m^{-2}	0.62**	0.72**	0.21	0.42*	0.4*				
Panicle weight m^{-2}	0.93***	0.79**	0.58*	-0.1	0.14	0.73**			
SPAD value	0.08	-0.15	0.15	-0.33	-0.47*	-0.42*	-0.1		
Straw yield	0.75**	0.69**	0.57*	-0.48*	0.02	0.19	0.58*	0.35	
1000-grain weight	0.15	0.5*	-0.6**	0.7**	0.04	0.34	0.21	0.03	0.12

*, **. *** Significantly different at 5, 1 and 0.1% respectively. (0 kg N ha^{-1} and 26666 plants ha^{-1}).

Table 5. Correlation between agronomical traits and physiological parameters measured in N2D2.

Variable	Grain yield	Leaf area index	Grain number per panicle	Plant height	Phyllochron	Panicle number per m^2	Panicle weight per m^2	SPAD value	Straw yield
Grain yield	1								
Leaf area index	0.79**								
Grain number/panicle	0.44*	0.24							
Plant height	0.21	0.41*	-0.13						
Phyllochron	-0.54*	-0.32	-0.2	-0.13					
Panicle number m^{-2}	0.66**	0.47*	-0.13	-0.12	-0.52*				
Panicle weight m^{-2}	0.96***	0.86***	0.38	0.3	-0.66**	0.64**			
SPAD value	0.24	0.71**	-0.01	0.03	0.01	0.24	0.36		
Straw yield	0.71**	0.85***	-0.02	0.66**	-0.26	0.44*	0.75**	0.38	
1000-grain weight	-0.16	0.2	-0.41*	0.66**	0.49*	-0.4*	-0.13	0.21	0.49*

*, **. *** Significantly different at 5, 1 and 0.1% respectively. N2D2 (178 kg N ha^{-1} and 53 333 plants ha^{-1}).

positively correlated with plant height in N2D2. The variables correlated to grain and straw yields will be used in variety Characterization.

Characterization of eight varieties for the traits studied

Principal Component Analysis (PCA-biplot) based on eight sorghum varieties in treatments N0D1 (Figure 3A) and N2D2 was conducted. In N0D1, the ACP-biplot shows three homogeneous groups. Dimensions 1 and 2 explain respectively 47.6% and 29.9% of total variation. Group 1 includes SOUMBA, FADDA and A12-79 varieties. It is characterized by less important variables. Group 2 is determined by a plant height and 1000-grain weight and is composed of TIEBILE and PABLO. Group 3 involves the varieties of type caudatum GRINKAN, C2_075-15 and C2_007-03 and is characterized by grain yield, straw yield, leaf area index, weight per m^2 and Grain number per panicle raised. In N2D2, the ACP-biplot indicates four homogeneous groups. Dimensions 1 and 2 explain respectively 49.2% and 26.6% of total variability (Figure 3B). Group 1, which includes the GRINKAN, SOUMBA and C2_007-03 varieties is characterized by a long phyllochron. Group 2, which involves the TIEBILE and PABLO varieties is defined by a large 1000-grain weight and plant height. Varieties of Group 3 are characterized by high grain number per panicle and consist of C2_075-15 and A12-79. Group 4, which is a single FADDA variety of guinea type is characterized by better grain yield, straw yield, leaf area index, panicle number per m^2 and panicle weight per m^2.

DISCUSSION

The study on the performance of eight sorghum varieties

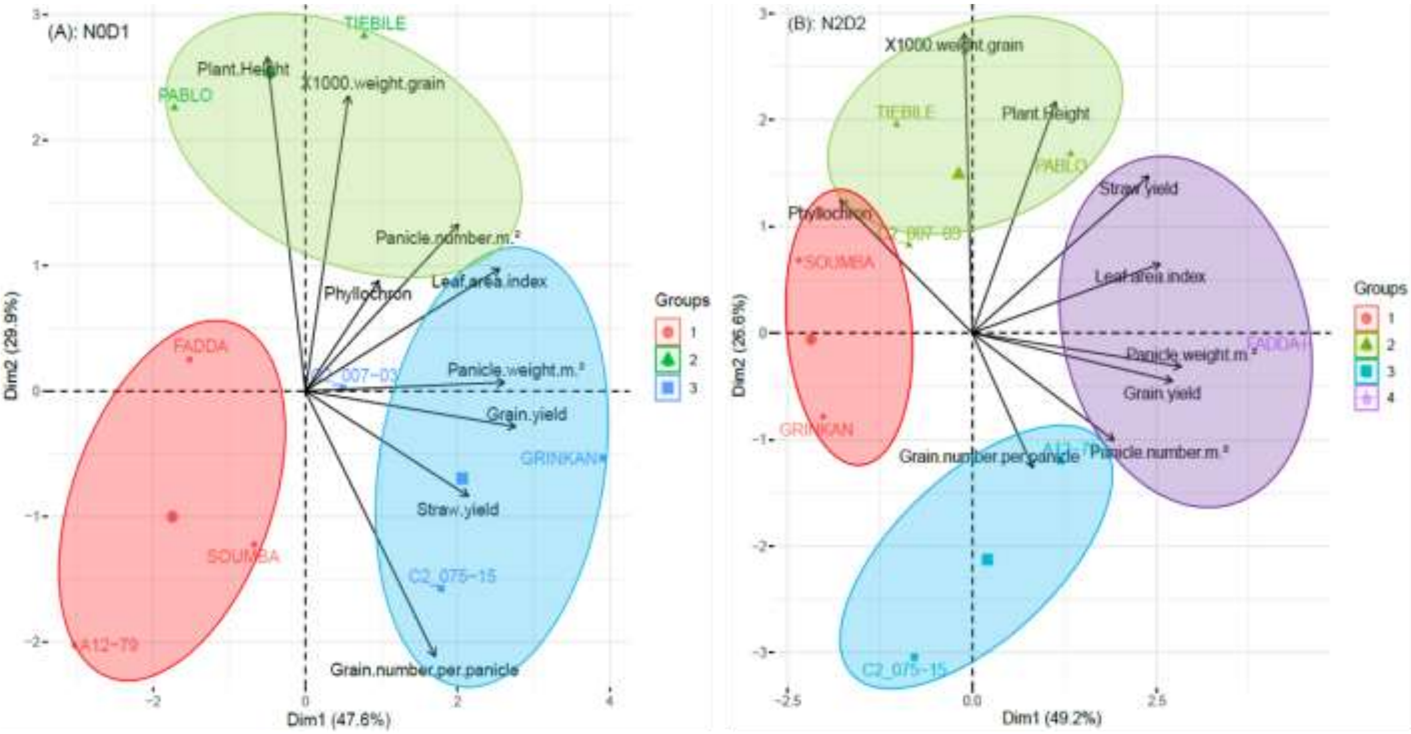

Figure 3. Principal component analysis (A: N0D1 and B: N2D2) with combination of variables and sorghum varieties at different planting densities and nitrogen fertilization. N0D1 (0 kg N ha^{-1} and 26666 plants ha^{-1}); N2D2 (178 kg N ha^{-1} and 53 333 plants ha^{-1})

at different plant densities and nitrogen fertilization enabled an understanding of the effect of intensification factors on sorghum grain and straw production in the Sudan-Sahelian zone in Mali. The response of the studied factors during the two-year trials may be due to rainfall distribution (Turgut et al., 2005; Oikeh et al., 2009) and soil heterogeneity. This could explain the decrease in grain yield (by 10%) and straw yield (by 72%) in the first trial as compared to the second. In this study, grain and straw yields increased with increasing plant density from D1 ((26666 plants ha^{-1})) to D2 (53 333 plants ha^{-1}) for all varieties tested. Nitrogen application also increased grain and straw yields from N0 (0 kg N ha^{-1}) to N2 (178 kg N ha^{-1}). Our results are similar to those reported by Moosavi et al. (2013) and Shrestha et al. (2018). However, the results also showed that grain yield and straw yield varied for all varieties at different plant density and nitrogen fertilization combinations. They also increased from N0D1 (0 KgN ha^{-1} and 26,666 plants ha^{-1}) to N2D2 (178 kg N ha^{-1} and 53 333 plants ha^{-1}). The highest grain yield under less intensive conditions (N0D1) was obtained with GRINKAN, C2_075-15, C2_007-03, TIEBILE and SOUMBA varieties than FADDA, PABLO and A12-19 varieties, which have been the lowest performing variety. GRINKAN variety of caudatum type produced the highest straw yield than FADDA, TIEBILE and PABLO varieties of guinea type except A12-79 in N0D1. Under intensive N2D2 treatment, FADDA variety recorded the highest grain yield (Figure 2B) and straw yield. These results suggest that response of varieties to different plant densities and nitrogen fertilization for grain and straw yields is highly variable and could be genetic. This shows that each variety or group of varieties needs an optimum nitrogen level and plant density to produce maximum grain and straw. Our results are consistent with studies conducted by Zhou et al. (2019). Shahrajabian et al. (2011) and Soleymani et al. (2011) also confirmed these findings in their study on sorghum.

Grain yield depends on the variety and growing conditions, in particular plant density and nitrogen fertilization. Its improvement depends on its components but also on physiological and growth traits. In this study, the panicle weight per m^2, leaf area index, straw yield and grain number per panicle parameters were most expressed in N0D1 (Table 4) and N2D2 (Table 5). These results clearly show that through these traits it is possible to increase grain yield under less intensive (N0D1) and intensive (N2D2) conditions. Researches conducted by Ogunlela and Okoh (1989), Buah et al. (2009), and Ajeigbe et al. (2018) reported similar results. But in N2D2, grain yield was strongly explained by panicle number per m^2. Moosavi et al. (2013) believed that at high plant density, emphasis should be placed on panicle number per m^2, because at high plant density, the grain number per panicle decreases even if grain yield per unit area increases. Straw yield in N0D1 and N2D2 was positively explained by leaf area index and panicle weight m^{-2}. There was also a positive correlation between straw yield, plant height and panicle number per m^2 in N2D2, but it was positively correlated by grain number per panicle in N0D1. This finding show that a selection made in favor of these traits can help us increase production of sorghum straw. According to Sahu et al. (2018), nitrogen application increases plant height and leaf area index in sorghum, which would be involved in increasing straw yield.

The variability observed under N0D1 and N2D2 treatments enabled the classification of eight varieties according to the traits studied. In N0D1, GRINKAN and C2_075-15 and C2_007-03 caudatum varieties (short size) produce the highest grain yield and are characterized by panicle weight per m^2, leaf area index, straw yield and grain number per panicle. In N2D2, FADDA (large size) guinea hybrid variety is the most performing and is characterized by grain yield, straw yield, leaf area index, panicle number m^{-2} and panicle weight per m^2. One of the specificities of this variety is its capacity to valorize nutrients and to develop an important tillering, a trait probably inherited from its parent Lata3. This would explain an increase in his traits in FADDA in N2D2. According to Lafarge et al. (2002) and Zand and Shakiba (2013), tillering is an important trait that leads to increased grain and straw yields in sorghum. In general, this trait has not been of much interest to the sorghum selection programs. However, it should now be one of the priorities of breeding programs to develop productive varieties with large tillering to intensify the crop sorghum.

Conclusion

This study showed that plant density and nitrogen fertilization on sorghum varieties significantly increased grain yield and straw yield. Grain yield in N0D1 and N2D2 was associated with panicle weight per m^2, leaf area index, straw yield, panicle number per m^2 and grain number per panicle. GRINKAN, C2_075-15 and C2_007-03 varieties produced maximum production of grains and straws in N0D1 (0 kg N ha^{-1} and 26666 plants ha^{-1}). These caudatum-type varieties may be recommended in less intensive sorghum production areas in Mali. FADDA variety produced the highest of grains and straws in N2D2 (178 kg N ha^{-1} and 53 333 plants ha^{-1}). Indeed, FADDA being a guinea-type hybrid variety could be recommended to the farmers for grain and fodder production because it is the variety that was better adapted to intensification.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Ajeigbe HA, Akinseye FM, Ayuba K, Jonah J (2018). Productivity and Water Use Efficiency of Sorghum [*Sorghum bicolor* (L.) Moench] Grown under Different Nitrogen Applications in Sudan Savanna Zone, Nigeria. International Journal of Agronomy 2018:1-11.

Akmal M, Hameed-Ur-Rehman, Farhatullah, Asim M, Akbar H (2010). Response of maize varieties to nitrogen application for leaf area profile, crop growth, yield and yield components. Pakistan Journal of Botany 42(3):1941-1947.

Arunakumari H, Rekha S (2016). Plant density and nitrogen in sorghum. International Journal of Science Natural 7(4):702-706.

Bazile D, Dembélé S, Soumaré M, Dembélé D (2008). Utilisation de la diversité variétale du sorgho pour valoriser la diversité des sols au Mali. Cahiers Agricultures 17(2):86-94.

Berenguer MJ, Faci JM (2001). Sorghum (*Sorghum Bicolor* L. Moench) yield compensation processes under different plant densities and variable water supply. European Journal of Agronomy 15:43-55.

Biswas M, Rahman AHMM, Ahmed F (2014). Effect of variety and planting geometry on the growth and yield of hybrid maize. Journal of Agriculture and Environmental Sciences 3(2):27-32.

Borrell AK, Mullet JE, George-jaeggli B, Oosterom EJ V (2014). Drought adaptation of stay-green sorghum is associated with canopy development , leaf anatomy , root growth , and water uptake. Journal of Experimental Botany 2014:1-13.

Brocke KV, Vaksmann M, Trouche G, Bazile D (2002). Préservation de l'agrobiodiversité du sorgho in situ au Mali et au Burkina Faso par l'amélioration participative des cultivars locaux. Ressources génétiques des mils en Afrique de l'Ouest. pp. 97-110.

Buah SSJ, Mwinkaara S (2009). Response of sorghum to nitrogen fertilizer and plant density in the guinea savanna zone. Journal of Agronomy 8(4):124-130.

Çalifikan S, Arslan M, ÜREM I, Çalifikan ME (2007). The Effects of Row Spacing on Yield and Yield Components of Full Season and Double-Cropped Soybean. Turkish Journal of Agriculture and Forestry 31:147-154.

Coulibaly A, Woumou K, Aune JB (2019). Sustainable Intensification of Sorghum and Pearl Millet Production by Seed Priming , Seed Treatment and Fertilizer Microdosing under Different Rainfall Regimes in Mali. Agronomy 9(664):1-14.

Ferraris R and Charles-Edwards DA (1986). A comparative analysis of the growth of sweet and forage sorghum crops . I dry matter production , phenology and morphology. Ausi. J. Agric. Res., 37: 495-512.

Fischera KS, Wilsonb GL (1975). Studies of Grain Production in Sorghum bicolor (L . Moench). Effect of planting density on growth and yield. Australian Journal of Agricultural Research 26:31-41.

Hanak-Freud H (2000). Au Burkina Faso , les céréales des cultures de rente. Agriculture et Développement 23:18-30.

Kante M, Rattunde HFW, Leiser WL, Nebié B, Diallo B, Touré AO, Haussmann BIG (2017). Can Tall Guinea-Race Sorghum Hybrids Deliver Yield Advantage to Smallholder Farmers in West and Central Africa ? Crop Science 57:1-10.

Kondombo CP, Tamini M, Barro A, Chantereau J (2017). Plant density effects on agromorphological traits and the yield of grain sorghum varieties in rainfed conditions in Burkina Faso. Agricultural Science Research Journal 7(6):221-229.

Kouyate Z, Wendt GW (1991). Water balance in the Sudano-Sahelian Zone (Proceedings of the Niamey Workshop, February 1991). IAHS Publ, 199:339-344.

Lafarge TA, Broad IJ, Hammer GL (2002). Tillering in grain sorghum over a wide range of population densities: Identification of a common hierarchy for tiller emergence, leaf area development and fertility. Annals of Botany 90(1):87-98.

Leibman M, Shryock JJ, Clements MJ, All M A, Loida PJ, Mcclerren AL, Mckiness ZP, Phillips JR, Rice EA, Stark SB (2014). Comparative analysis of maize (*Zea mays*) crop performance : natural variation , incremental improvements and economic impacts. Plant Biotechnology Journal 12:941-950.

Li Y, Cui Z, Ni Y, Zheng M, Yang D, Jin M (2016). Plant density effect on grain number and weight of two winter wheat cultivars at different spikelet and grain positions. PLoS ONE 11(5):1-15.

Moosavi SG, Seghatoleslami JM, Arefi R (2013). Effect of N fertilization and plant density on yield and yield components of grain sorghum under climatic conditions. Scientia Agriculturae 3(1):1-8.

Ogunlela VB, Okoh PN (1989). Response of three sorghum varieties to N supply and plant density in a tropical environment. Fertilizer Research 21(2):67-74.

Oikeha S, Toure A, Sidibe B, Nianga A, Semona M, Sokeia Y and Marikoa M (2009). Responses of upland NERICA rice varieties to nitrogen and plant density. Archives of Agronomy and Soil Science 55(3):301-314.

Sahu H, Tomar GS, Nandeha N (2018). Effect of planting density and levels of nitrogen on yield and yield attributes of sweet Sorghum (Sorghum bicolor [L.] Moench) Varieties. International Journal of Chemical Studies 6(1):2098-2101.

Shahrajabian MH, Soleymani A, Naranjani L (2011). Grain yield and forage characteristics of forage sorghum under different plant densities and nitrogen levels in second cropping after barley in Isfahan , Iran grain yield and forage characteristics of forage sorghum under different plant densities and nitrogen levels in second cropping after barley in Isfahan, Iran. Research on Crops 12(1):68-78.

Sher A, Ansar M, Ijaz M, Sattar A (2016). Proximate analysis of forage sorghum cultivars with different doses of nitrogen and seed rate. Turkish Journal of Field Crops 21(2):276-285.

Shrestha J, Nath Yadav D, Prasad Amgain L, Prasad Sharma J (2018). Effects of nitrogen and plant density on maize (*Zea mays* L.) phenology and grain yield. Current agriculture research Journal 6(2):175-182.

Soleymani A, Shahrajabian MH, Naranjani L (2011). The effect of plant density and nitrogen fertilization on yield , yield components and grain protein of grain sorghum The effect of plant density and nitrogen fertilization on yield , yield components and grain protein of grain sorghum. Journal of Food, Agriculture and Environment 9(3-4):244-246.

Srinivas G, Satish K, Madhusudhana R, Nagaraja Reddy R, Murali Mohan S, Seetharama N (2009). Identification of quantitative trait loci for agronomically important traits and their association with genic-microsatellite markers in sorghum. Theoretical and Applied Genetics 118(8):1439-1454.

Tajul MI, Alam MM, Hossain SMM, Naher K, Rafii MY, Latif MA (2013). Influence of plant population and nitrogen-fertilizer at various levels on growth and growth efficiency of maize. The Scientific World Journal 2013:1-9.

Trouche G, Da S, Pale G, Sohoro A, Ouedraogo O, Den G (2001). Evaluation participative de nouvelles varietes. Dans sélection participative, Hocdé, Lançon J, Trouche G (eds). Cirad-INERA Montpellier pp. 36-55.

Turgut I, Bilgili U, Duman A, Acikgoz E (2005). Production of sweet sorghum (Sorghum bicolor L. Moench) increases with increased plant densities and nitrogen fertilizer levels. Acta Agriculturae Scandinavica Section B: Soil and Plant Science 55(3):236-240.

Vaksmann M, Kouressy M, Chantereau J, Bazile D, Sagnard F, Touré A, Sanogo O, Diawara G, Danté A (2008). Utilisation de la diversité génétique des sorghos locaux du Mali. Cahiers Agricultures 17(2):140-145.

Venables WN, Smith DM, R Core Team (2019). A programming environment for data analysis and graphics. This manual is for R, version 3.6.2. pp.1-94.

Xie H, Huang Y, Chen Q, Zhang Y, Wu Q (2019). Prospects for Agricultural Sustainable Intensification. A Review of Research Land 8(11):157.

Zand N, Shakiba MR (2013). Effect of plant density and nitrogen fertilizer on some attribute of grain sorghum (*sorghum bicolor* (l.) moench). International journal of Advanced Biological and Biomedical Research 1(12):1577-1582.

Zhou C, Huang Y, Jia B, Wang S, Dou F (2019). Optimization of nitrogen rate and planting density in Northeast China for improving the grain yield of different rice genotypes. Agronomy 555(9):1-18.

Zougmoré R, Zida Z, Kambou NF (2003). Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. Soil and Tillage Research 71:143-149.