The Journal of Agricultural Science

cambridge.org/ags

Climate Change and Agriculture Research Paper

Cite this article: Traoré A, Gozé E, Gérardeaux E, Diouf L, Ndour A, Ndiaye S, Oumarou P, Loison R (2023). Optimal choice of cotton cultivar for rainfed conditions in Sahelo-Sudanian climate with late planting: a case study in Senegal. *The Journal of Agricultural Science* **161**, 469–476. https://doi.org/10.1017/S0021859623000370

Received: 24 November 2022
Revised: 12 June 2023
Accepted: 4 July 2023
First published online: 25 July 2023

Keywords:
Genotype × planting date interaction; *Gossypium hirsutum* L; robust statistical analysis; seed cotton yield; sensitivity; Sub-Saharan Africa; yield resilience

Corresponding author:
Romain Loison;
Email: romain.loison@cirad.fr

Optimal choice of cotton cultivar for rainfed conditions in Sahelo-Sudanian climate with late planting: a case study in Senegal

Abdou Traoré[1], Eric Gozé[2], Edward Gérardeaux[2], Latyr Diouf[3], Abdoulaye Ndour[4], Saliou Ndiaye[5], Palaï Oumarou[6,7] and Romain Loison[8,9]

[1]CIRAD, UPR AIDA/SODEFITEX/ISRA, CRA-Tambacounda, Tambacounda, Senegal; [2]CIRAD, UPR AIDA, F-34398 Montpellier, France; [3]CRA-Tambacounda, ISRA, Tambacounda, Senegal; [4]SODEFITEX, Tambacounda, Senegal; [5]ENSA, Université Iba Der Thiam, Thies, Senegal; [6]SODECOTON, Garoua, Cameroon; [7]Cameroun/IRAD, Garoua, Cameroon; [8]CIRAD, UPR AIDA, F-34398 Montpellier, France and [9]SODEFITEX, Dakar, Senegal

Abstract

Late planting due to erratic onset of the rainy season is becoming more frequent in the Sahelo-Sudanian climate where cotton is grown, causing seed cotton yield (SCY) loss and higher risk of drought at the end of the crop cycle. Therefore, cultivars should be adapted to late (from July 10) planting date (PD) in Senegal. The aim of this study was to analyse the interaction between genotypes and PD on SCY in Senegal under rainfed conditions. Field experiments were conducted in 2018 and 2019 using a split-plot design (two PDs, eight cultivars) at three experimental stations. Robust analysis of SCY was used to moderate the effect of potential outliers. The average SCY was 1404 kg/ha under early planting, and 714 kg/ha under late planting. The best SCY was obtained under early planting conditions, in environments with good rainfall. The loss due to late planting was significantly affected by cultivar choice. None of the cultivars performed best under both early and late PD. Under early PD, cultivar CS 50 gave the best SCY, while under late PD it was cultivar IRMA Q302. The best performing cultivar on average depended on the proportion of early plantings. A model was developed to identify the best overall cultivar based on the expected proportion of early planting, as a decision support tool for the cotton development company, if only one cultivar is released. The benefit of releasing a second cultivar for late-planted fields is considered.

Introduction

In Senegal, cotton (*Gossypium hirsutum* L) is the second most important cash crop after groundnut (Diouf *et al.*, 2019), despite a recent decline in planted areas and yields (Diouf *et al.*, 2017). According to SODEFITEX (the national cotton development company in Senegal), in 2018–2019 cotton was cultivated on 21 735 ha for a national production of 15 122 metric tons, and an average seed cotton yield of 696 kg/ha (SODEFITEX 2019). As in other parts of West Africa, cotton cultivation in Senegal is carried out under rainfed conditions, mainly by smallholders on small plots (Bagayoko, 2013). This production system is generally manual, labour-intensive (UNCTAD and CNUCED 2016) and not input-intensive (Fok, 2006). The cotton production area is located in the South-eastern part of the country. Senegal's climate is Sudan-Sahelian and is characterized by a long dry season from November to May and a monomodal rainy season from June to October. The dry spells are long and frequent at the beginning of the rainy season and useful rains (>15 mm) are only regular around the end of July to beginning of August (Ndour, 2018). Early planting is essential for good yields but unpredictable early rains and labour constraints make it difficult for farmers to plant at the right time, before July 10 (Ndour, 2018). Consequently, late planting is frequent and has a negative impact on yield (Sekloka *et al.*, 2015; Loison *et al.*, 2017), especially in Sub-Saharan Africa (SSA) under rainfed conditions (Cao *et al.*, 2011).

West Africa is expected to experience an increase in temperature and a reduction in rainfall (Guan *et al.*, 2017; Gaetani *et al.*, 2020). This climate is likely to have a negative impact on rainfed cotton production in West Africa (ITC 2011). Even under the current climate, there is no widely cultivated cultivar adapted to all environments of the Senegalese cotton basin, especially in the case of drought (Ndour *et al.*, 2017). Therefore, cultivars adapted to the current Senegalese agro-climatic conditions, with a late onset of the rainy season and high rain irregularity should be better adapted to the future climate. Adaptation is also necessary for labour constraints that imply frequent late planting. The appropriate choice of planting dates (PDs), and of cultivars adapted to late planting could increase expected yields in SSA (Cao *et al.*, 2011; Traore *et al.*, 2014). Interactions between PDs and cotton cultivars have been studied mainly under European conditions (Tuttolomondo *et al.*, 2020). To our knowledge, the interaction between genotype and PD has never been studied for cotton in Senegal. As it may vary according to environmental conditions, this interaction is best studied through multilocal and multiannual trials (Lacape, 1998). Thus, experimental trials were set up in Senegal during two consecutive rainy seasons in 2018 and 2019 in three study sites. A linear mixed-effects model is most suitable for studying this experimental design. In the trials, problems of soil heterogeneity which impacted on the measured yield were encountered. Therefore, our data analysis uses a robust estimation method (Koller, 2016). High soil heterogeneity is a common feature in SSA (Lark *et al.*, 2020). The objectives of this study were (i) to identify cultivars with high seed cotton yield (SCY) potential under early and late PDs, and (ii) to support decision makers in SSA in their choice of the best cotton cultivars in the context of mixed early and late PDs.

Materials and methods

Experimental sites

The experimental trials were set up at three research stations during two growing seasons (2018 and 2019). The three research stations were Koussanar, Vélingara and Kédougou (Table 1). Meteorological data were recorded at each location within 50 m of the plot by automatic weather stations (iMETOS® IMT280 or ATMOS 41). Summaries of climatic data were reported from the PD to the end of growing season.

The top 30 cm of the soil were sampled and analysed in the IMAGO laboratory of the Institut de Recherche pour le Développement in Dakar. In Kédougou, all soil had very low organic matter content with a maximum value of 1.45%. The soil classification according to the USDA system was silty clay loam in Kédougou, clay in Vélingara and a sandy loam in Koussanar (Table 1).

Experimental design

At each site, the field experiment was set up in a split plot with two factors (PD and cultivar) and three replicates. The two PDs were randomly assigned to the main plots using a complete block design (P1: early planting as soon as possible and P2: as soon as possible in the late planting window). The eight cultivars were then randomly assigned to sub plots within the main plots. These cultivars were chosen a priori for their wide range of response to drought (Table 2).

For all growing environments, each sub plot consisted of six rows (10 m each). The planting configuration was 0.80 m between the lines and 0.25 m between hills. In all growing environments except Koussanar in 2018, fertilization consisted of 250 kg/ha of complex granular fertilizer (NPKSB 14-23-14-5-1 in 2018 and NPKSBCaO 14-18-18-5-1-2.5 in 2019) and 100 kg/ha of urea at 46% N. In Koussanar in 2018, the complex fertilizer was supplied at 200 kg/ha and the urea at 50 kg/ha. In every site, complex fertilizer was applied at thinning and urea between 40 and 45 days after planting. The pesticides were used according to a single calendar (based on PD) to have the same application dates (in days after planting) and application rates. Air-dried SCY from each plot was measured on the three central lines and converted into kg/ha for statistical analysis.

Data analysis

A mixed model (Eqn 1) was adjusted using residual maximum likelihood (REML) to the square root of the SCY to ensure homoscedasticity of the residuals, because this was not obtained with the untransformed yield. The effects of genotype, PDs, and their interaction were considered as fixed, and the environment, block and main plot effects with their interactions were considered as random. The mixed model is:

$$Y_{ijkl} = \mu + g_i + p_j + (gp)_{ij} + E_k + B(E)_{lk} + (gE)_{ik} + (pE)_{jk} + M(pE)_{jkl} + \varepsilon_{ijkl} \quad (1)$$

where Y_{ijkl} is the measured square root of SCY of the *i*th genotype for the *j*th PD in the *k*th environment [location × year] and the *l*th block;

μ is the overall mean;
g_i is the effect of the *i*th genotpe;
p_j is the effect of the *j*th PD;
$(gp)_{ij}$ is the effect of the interaction of the *i*th genotype with the *j*th PD;
E_k is the random effect of the *k*th environment;
$B(E)_{lk}$ is the random effect of *l*th block in the *k*th environment;
$(gE)_{ik}$ is the random effect of the interaction of the *i*th genotype with the *k*th environment;
$(pE)_{jk}$ is the random effect of the interaction of the *j*th PD with the *k*th environment;
$M(pE)_{jkl}$ is the random effect of the main plot with the *j*th PD within the *l*th block in the *k*th environment (main plot effect);
and ε_{ijkl} is experimental error.

The estimation of the effects in a mixed model using REML may be badly affected by outliers, and the detection of outliers is prone to error. Robust statistical methods are designed to address this problem in the mixed model (Eqn 1) to reduce the effect of outliers. A robust method was used to estimate the parameters of the mixed model. Subsequently, cultivar SCYs for any proportion of early planting were estimated using linear estimation methods. Finally, the estimated means and the minimum significant differences using Tukey tests with 5% experiment-wise risk were computed and plotted. Only the tests for fixed and random effects were performed using a non-robust method.

The rate of late planting at the country level was based on actual data collected by SODEFITEX between 2000 and 2022. The slope of the linear model of late planting proportion as a function of the campaign year was evaluated for trend analysis.

A situation where a choice has to be made between disseminating one or two varieties in a given area, based on the early and late planting rates measured in the area was considered. Then, simulations were conducted to determine the potential production and monetary gains when changing from the current cultivar Stam 129A to one or two new cultivars. Monetary gains were computed based on the costs of 2020 from the SODEFITEX: A cost of inputs for seeds, fertilizer, herbicides, insecticides and battery for application devices of 125 820 FCFA/ha and a price of seed cotton of 300 FCFA/kg.

All statistical analyses were performed using R software version 4.3.1 (2023-06-16) with the packages lmerTest (Kuznetsova *et al.*, 2017) and robustlmm (Koller, 2016) for mixed modelling with REML and robust estimation methods, respectively. The packages

Table 1. Description of the 12 growing environments used in the study

Research station	Coordinates	Sand (%)	Clay (%)	Silt (%)	Soil texture[a]	Year	Planting date	Planting code	Environment code	T_{min} (°C)	T_{max} (°C)	Rainfall (mm)[b]
Kédougou	12°39′N,	19.2	33.7	47	Silty clay loam	2018	June 28	P1	KG18P1	21.6 (2.9)[c]	31.8 (2.4)[c]	1096
	12°7′W						July 19	P2	KG18P2	20.3 (4.2)	32.2 (2.4)	984
						2019	July 5	P1	KG19P1	20.7 (3.9)	32.7 (2.6)	1268
							July 20	P2	KG19P2	20.4 (4.0)	32.8 (2.6)	1115
Vélingara	13°9′N,	27.9	48	24.6	Clay	2018	July 9	P1	VL18P1	22.8 (1.3)	31.0 (1.7)	801
	14°2′W						July 30	P2	VL18P2	22.0 (2.2)	30.9 (1.7)	656
						2019	June 30	P1	VL19P1	22.6 (2.0)	32.7 (2.1)	970
							July 15	P2	VL19P2	22.5 (1.5)	32.7 (2.7)	835
Koussanar	13°55′N,	59.3	12.7	28.4	Sandy loam	2018	June 30	P1	KO18P1	23.2 (2.3)	33.2 (2.7)	412
	14°3′W						July 17	P2	KO18P2	21.9 (3.6)	33.6 (2.9)	382
						2019	July 7	P1	KO19P1	23.0 (2.9)	33.4 (2.6)	469
							August 19	P2	KO19P2	20.4 (3.9)	34.3 (3.1)	349

KD, Kédougou; KO, Koussanar; VL, Vélingara.
[a]Classification according to the USDA method based on data over the 0–30 cm horizon.
[b]Rainfall = total rainfall during the trial (from planting to harvest).
[c]The standard deviation of the mean is indicated in parenthesis.

Table 2. Name, geographic origin and traits of cultivars used in the study

Cultivar name	Origin	Traits
Stam 129A	Togo	Reference, widely cultivated in Senegal, potential seed cotton yield of 3000 kg/ha, cycle of 120 days, cultivar released in 1998.
CS 50	Australia	Drought sensitive
TAMCOT CAMD-S-75-C	USA	Long vegetative phase and short reproductive phase
BUJA	Ivory Coast	Strong leaf reduction in drought conditions
ALLEN 51–106	Chad	Short vegetative phase and long reproductive phase
IRMA L484	Cameroon	Drought tolerant, cultivar released in 2006.
IRMA Q302	Cameroon	Drought tolerant, cultivar released in 2012.
SIOKRA L23	Australia	Drought tolerant and okra-leaf

stringr and plyr (Wickham, 2011) were used for data manipulation, and the package ggplot2 (Wickham, 2016) was used for graphical representation of the results. The R script used for this study is provided as Supplementary material (Sup. 1).

Results

Weather data

In the 12 environments, the minimum temperature ranged from 20.3 to 23.2°C (Table 1). These temperatures are higher than 13°C, which is the base temperature for cotton (Crétenet and Gourlot, 2016). The range of cumulative rainfall observed in this study in early planting conditions (412 to 1268 mm) covers the existing range observed in most cotton producing area in SSA (~500 to 1200 mm observed in Mali and Cameroon) (Sultan *et al.*, 2009; Ba *et al.*, 2019; Sarr *et al.*, 2021). In SSA, even though the water requirements of the cotton plant vary greatly according to the intensity of sunshine, air relative humidity, runoff and irregularity of rainfall, less than 700 mm of rainfall is considered insufficient (Sément, 1986). The cumulative rainfall from planting to harvest ranged from 349 to 1268 mm in this study. In all the environments of Koussanar (KO18P1, KO18P2, KO19P1, KO19P2) and for the late PD in Vélingara in 2018 (VL18P2), very low cumulative rainfall was observed during the growing period (412, 382, 469, 349 and 656 mm, respectively). Whereas, in Kedougou, cumulative rainfalls observed during the growing period were relatively sufficient, with a minimum of 984 mm in late PDs.

Table 4. Estimated variances and tests of the random factors of the linear mixed model of square root of seed cotton yield

Source	Variance	Standard deviation	*P* value*
Environment	19.64	4.43	0.12731
Environment × Cultivar	0.61	0.78	0.38987
Environment × Planting date	10	3.16	0.00790
Blocks within environments	0	0	–
Sub-blocks within environments	5.7	2.39	–
Residual	15.21	3.9	–

**P* values were calculated based on likelihood ratio tests of model reductions.

Average performance of genotypes, planting dates, environments and interaction effects

F tests were performed after REML estimation (without a robust method). The square root of the SCY of the eight cultivars at early and late PDs showed significant effects of cultivar, PD and of their interactions ($P < 0.01$, Table 3).

Random factors were tested using a likelihood ratio test for model reductions (Table 4). There was no significant effect of the environment nor significant interaction between cultivar and environment. However, there was a strong interaction between the environment and the PD ($P = 0.00790$). This interaction was due to one environment, where late planting had virtually no impact on yield due to frequent end-of-season rainfall.

The average SCY was 1404 kg/ha under early planting and 714 kg/ha under late planting (Fig. 1). None of the cultivars outperformed the others both under early and late planting conditions. Under early planting conditions, CS 50 was the best performing (1588 kg/ha), while ALLEN 51-106 was the worst (1137 kg/ha). Under late planting conditions, IRMA Q302 was the best performing genotype (839 kg/ha), whereas BUJA was the worst (592 kg/ha). The difference between the best and worst cultivars was larger under early planting conditions than under late planting.

Appropriate choice of genotypes for extension purposes

At the field scale, a farmer should use CS 50 for early plantings and IRMA Q302 for late plantings. At the ginning plant level, a ginner may not want to handle deliveries of different cultivars with different technological characteristics and risk to mix fibres of different qualities. The development company may then decide to release only one cultivar, to be used regardless of the PD. The problem is then to choose this cultivar in order to maximize the

Table 3. Tests of fixed factors of the linear mixed model of square root of seed cotton yield

Source	DF	SS	MS	Den DF	*F* value	*P* value
Planting date	1	414.6	414.6	5	27.2	0.00340
Cultivar	7	341.0	48.7	35	3.2	0.00997
Planting date ×Cultivar	7	400.8	57.3	203	3.8	0.00074

Note: DF: degree of freedom, SS: sum of square, MS: mean of square, Den DF: denominator degree of freedom approximated with Satterthwaite's method.

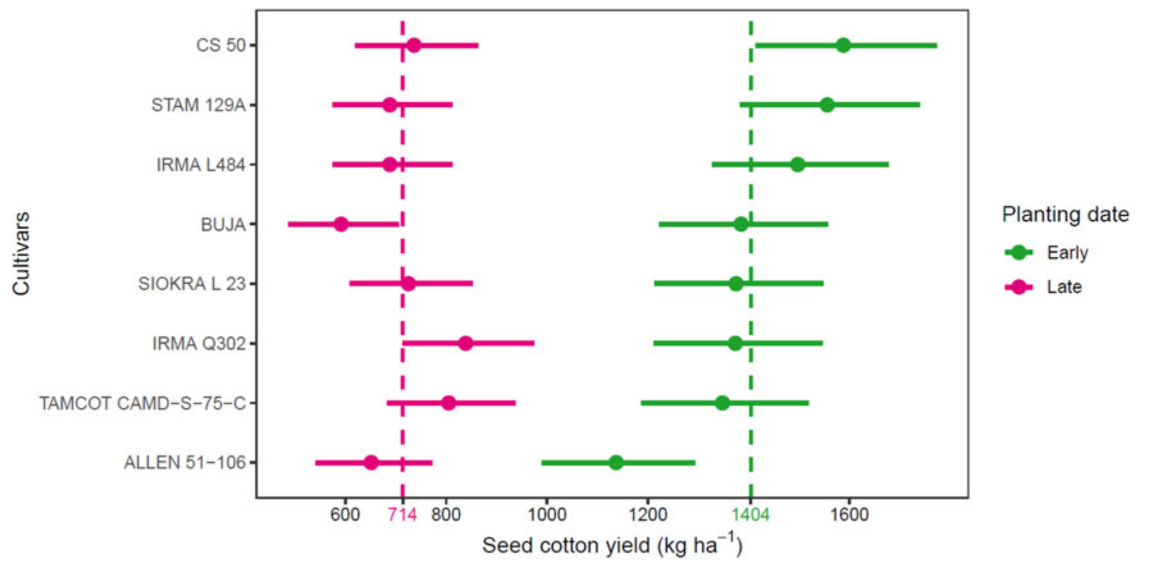

Figure 1. Robust estimation of seed cotton yield of the eight cultivars studied under early and late planting dates conditions. Cultivars are ranked according to early planting performance. The vertical dashed lines are the average seed cotton yield across cultivars under early (1404 kg/ha) and late planting dates (714 kg/ha). Within each planting date, cultivars with non-overlapping bars are significantly different after Tukey's Honest Significant Difference (HSD) test at 95%.

production on average, given an expected proportion of late plantings.

The proportion of late plantings in Senegal has been highly variable from 2000 to 2019, with no discernible trend (Fig. 1). Thus, the best bet for the coming year is an average late planting rate of 23.9%. Using linear estimates with this average proportion, the best cultivar under the 23.9% average proportion of late planting was CS 50 with 1355 kg/ha, while the worst was ALLEN 51–106 with 1009 kg/ha and a ranking can be calculated (Fig. 3). As the actual proportion varies much from year to year, Fig. 4 helps us check that the CS 50 superiority is stable over the range of variation of late planting proportion (4 to 53%, Fig. 2). Tukey's honest significant difference (95% MSD) is plotted with bars on top of the figure to represent the uncertainty of multiple comparisons. For any proportion of early planting, two cultivars had different yields when the difference was greater than the corresponding MSD (Fig. 4). For example, at 23.9% late planting, four cultivars performed better than ALLEN 51–106.

The monetary income improvement to farmers that could be generated by the choice of new cultivars depends on the possibility of promoting either two cultivars, or only one cultivar (as is currently the case). In the case of two cultivars, when compared with the current cultivar Stam 129A, the cultivar CS 50 would be a suitable choice for early planting and IRMA Q302 for late planting. These could generate an expected gain of 9585 FCFA/ha (14.6 €/ha) for early planting farmers, and 45 132 FCFA/ha (68.8 €/ha) for late planting farmers (Table 5). In the case of only one cultivar, the optimal choice is cultivar CS 50 and the expected income gain remains unchanged for early planting farmers, but drops to 14 411 FCFA/ha (21.5 €/ha) for late planting farmers.

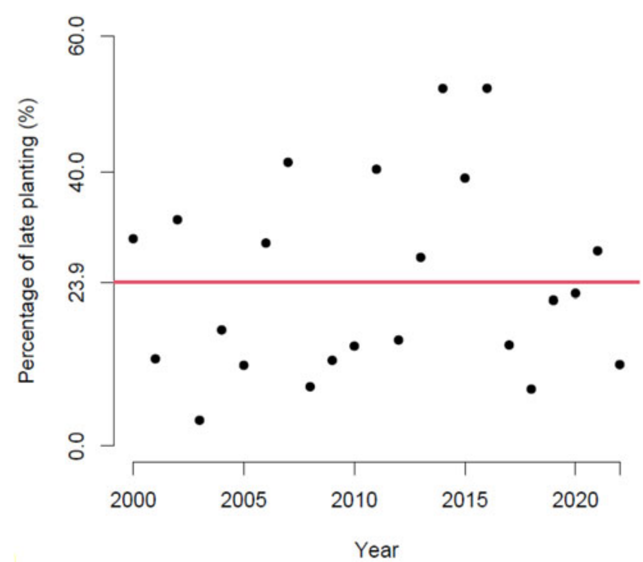

Figure 2. Percentage of late planting dates of cotton in Senegal from 2000 to 2022. The horizontal line at 23.9% is the average proportion of late planting area at the country level.

Discussion

Overall, the best yields were obtained with early planting (P1), which confirms that late plantings (P2) cause significant losses in SCY, consistent with other findings (Taner *et al.*, 2006; Khan *et al.*, 2017; Loison *et al.*, 2017). Moreover, cotton cultivars that withstand late PDs should provide better expected yield elsewhere in SSA.

The cultivar CS 50 showed a large difference in SCY between early and late planting (Figs 1 and 4). This is consistent with a previous description of CS50 as a late-maturing cultivar with irregular performance in dry areas in Australia (Stiller *et al.*, 2005). Cultivar Stam 129A, which is cultivated throughout the Senegalese cotton basin, confirms its sensitivity to water deficit as previously observed (Gnofam *et al.*, 2014). This is the reason why the differences in SCY between early and late planting for cultivar Stam 129A are large (2nd best in early planting and below average in late planting; Figs 1 and 4).

https://doi.org/10.1017/S0021859623000370 Published online by Cambridge University Press

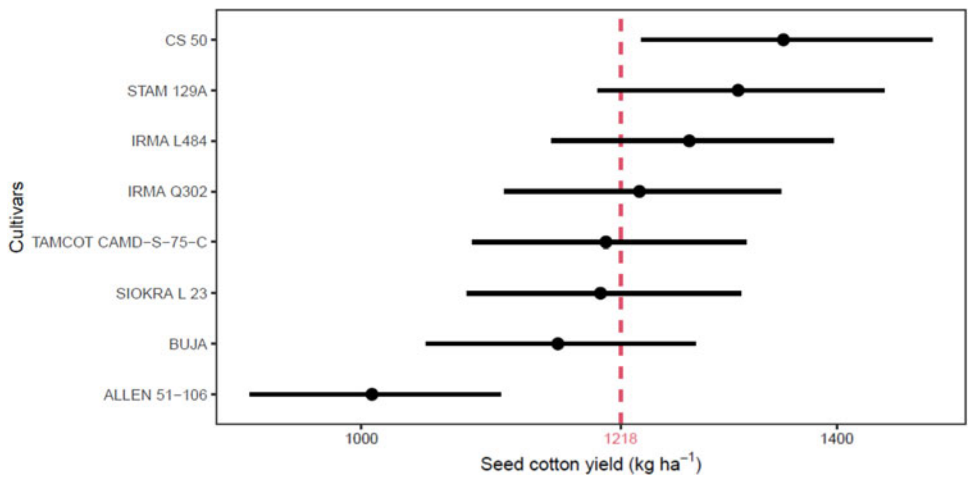

Figure 3. Robust estimation of seed cotton yield for a proportion of late planting of 23.9%. Cultivars with non-overlapping bars are significantly different after Tukey's honest significant difference (HSD) test at 95%.

A very ancient cultivar, ALLEN 51–106 showed poor performance and high phenotypic stability. These results confirmed that low agronomic performance is associated with phenotypic stability (Ndiaye *et al*., 2019). Based on the difference between performances in early and late planting conditions, and the absence of other GxE interaction, the results indicate that the cultivar IRMA Q302 is one of the most resilient cultivars (along with ALLEN 51–106) of the eight cultivars tested. In addition, it had a potential yield under early planting which was slightly lower than the average yield of all cultivars (Fig. 1). This result is similar to previous findings that genotypes with good phenotypic stability could also have good production potential (Farias *et al*., 2016). The cultivar IRMA Q302 was the most productive under conditions of late planting. These results corroborate those of breeders from Cameroon who have extended IRMA Q302 to replace IRMA L484 in the driest region of the Cameroonian cotton production basin (Oumarou *et al*., 2014). Cultivar CS 50 was described as drought sensitive and was not among the best cultivars under late planting conditions. In addition, CS 50 has a determinate growth pattern, while IRMA Q302 has an indeterminate growth pattern. The relative performance of these two cultivars under early or late planting conditions confirms that indeterminate growth pattern enables cotton plants to respond appropriately to adverse conditions (Cao *et al*., 2011).

Senegalese farmers are often unable to complete planting within the best (early) planting period because of several constraints, including irregular rains and unavailability of labour. For example, during the 2019–2020 season, cotton was cultivated on 15 814 ha in Senegal, distributed as follows: 12 446 ha of early planting (emergence until July 15) and 3368 ha of late planting (emergence after July 15). At the scale of the cotton basin, the use of cultivar CS 50 for early planting and IRMA Q302 for late planting could have generated an increase of 906 metric tons, whereas the use of CS 50 only generated 560 metric tons

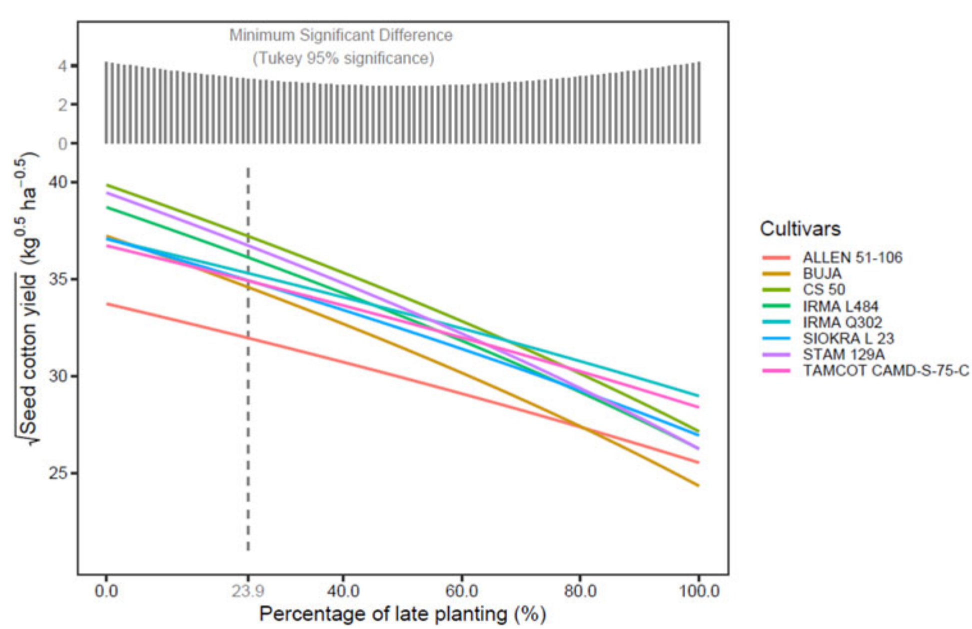

Figure 4. Seed cotton yield robust estimation of the eight cultivars as a function of the proportion of late planting.

https://doi.org/10.1017/S0021859623000370 Published online by Cambridge University Press

Table 5. Impact on the farmer income and global seed cotton production in Senegal of the replacement of current cotton cultivar STAM 129A by one cultivar (CS 50) or two (CS 50 for early plantings and IRMA Q302 for late plantings)

Strategy	Condition	Cotton area in 2019[a] (ha)	Area weight (%)	Cultivar	Extra SCY vs. STAM 129A[b] (kg/ha)	Seed cotton purchase price[c] (FCFA/kg)	Extra farmer income (FCFA/ha)	Extra country production (metric tons)
1 Cultivar	Early planting	12 466	78.7	CS 50	31.9	300	9585	398
	Late planting	3368	21.3	CS 50	48.0	300	14 411	162
	Total	15 814	100					560
2 Cultivars	Early planting	12 466	78.7	CS 50	31.9	300	9585	398
	Late planting	3368	21.3	IRMA Q302	150.4	300	45 132	507
	Total	15 814	100					906

[a]Based on the Senegalese cotton belt area in 2019–2020.
[b]Extra seed cotton yield (SCY) with alternative cultivar compared to the current cultivar Stam 129A.
[c]This price is the one used since 2017 up to 2022.

of seed cotton (Table 5). In other parts of SSA, it is common practice to plant several cultivars at the same time, such as in Cameroon (Oumarou *et al.*, 2019), Benin and Mali (PR-PICA 2019).

Based on the findings of the current study, it was recommended that cultivars are selected according to the targeted planting windows. In terms of the design of experiments, three replicate, three sites and 2 years of experiments with only two factors were used. In SSA, where landscape and soil heterogeneity are high and financial resources are limited, it is better to reduce the number of treatments and increase the number of replications to have good statistical power in the analysis of the trials (Lark *et al.*, 2020). Hence, further studies should optimize the number of treatments and replicate.

The focus of this study was on SCY and not on fibre quality. Further studies should ensure that the gain in SCY is not achieved at the expense of the fibre quality. With climate change, high temperature tolerance shall be of increasing importance and cultivars should be screened for that tolerance, which is correlated with SCY (Farooq *et al.*, 2021). Furthermore, the current study focused on the genetic aspects of improving cotton cropping systems. Intercropped cotton has proven its potential to increase resource use efficiency (Wang *et al.*, 2020), SCY (Chi *et al.*, 2019) and could even benefit subsequent cereal crops (Rusinamhodzi *et al.*, 2006). This pathway should be further investigated in Senegal and in other cotton-producing countries in SSA.

Conclusion

The findings of this study show that none of the cultivars outperformed the others under both early and late planting conditions. Therefore, the extension of at least two cultivars, CS 50 for early planting and IRMA Q302 for late planting is recommended. For cost and logistics reasons, if only one cultivar can be used in Senegal, a tool to support the choice of the best cultivar for any chosen proportion of early planting was provided. This decision support tool if employed in Senegal could improve farmers' income and country wide production.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859623000370

Acknowledgments. The authors are thankful to Régis Diouf, Malang Camara, Abdoulaye Senghor, Sory Baldé, Sékou Sadio, Maguette Diop and Moussane Cissé for their major contribution in data collection, and Sarah Alobo Loison for editing the English of the paper.

Author's contributions. Conceptualization: A.T. and R.L.; Methodology: Er.G. and R.L.; Software: Er.G. and R.L.; Validation: Er.G. and R.L.; Formal analysis: Er.G., R.L. and A.T.; Investigation: A.T.; Resources: A.T.; Data curation: A.T.; Writing original draft preparation: A.T. and R.L.; Writing – review and editing: A.T., R.L., Er.G. Ed.G., A.N., S.N. and P.O.; Visualization: R.L.; Supervision: R.L., Ed.G., S.N. and L.D.; Project administration: A.T., Ed.G., A.N. and R.L.; Funding acquisition: A.T. and A.N. All authors have read and agreed to the published version of the manuscript.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interest. None.

Ethical standards. Not applicable.

References

Ba A, Konipo O, Diarrisso T, Dembele B, Kone AK, Konte MS and Coulibaly D (2019) Déterminants des stratégies de diversification des cultures dans les exploitations agricoles en zone cotonnière du Mali.

Bagayoko K (2013) *L'importance et L'avenir du Coton en Afrique de L'Ouest: Cas du Mali*. Grenoble, France: Université de Grenoble.

Cao T-V, Oumarou P, Gawrysiak G, Klassou C and Hau B (2011) Short-season cotton (*Gossypium hirsutum*) may be a suitable response to late planting in sub-Saharan regions. *Field Crops Research* **120**, 9–20.

Chi B, Zhang Y, Zhang D, Zhang X, Dai J and Dong H (2019) Wide-strip intercropping of cotton and peanut combined with strip rotation increases crop productivity and economic returns. *Field Crops Research* **243**, 107617.

Crétenet M and Gourlot J-P (2016) Le cotonnier. Quae. ISBN: 978-2-7592-2379-4.

Diouf FBH, Sall M, Dia D, Gueye M, Sy MR and Sarr M (2017) Etat des lieux de l'amélioration du cotonnier au Sénégal et perspectives de recherches. In M. Soumaré & M. Havard, eds. Les zones cotonnières africaines. Dynamiques et durabilité. Actes du Colloque de Bamako. Novembre 2017. Bamako, pp. 24–36.

Diouf N, Mbaye MS, Gueye M, Dieng B, Bassene C and Noba K (2019) La flore adventice des cultures cotonnières dans le Sénégal Oriental et en Haute Casamance. *International Journal of Biological and Chemical Sciences* **13**, 1720.

Farias FJC, Carvalho LP, Silva Filho JL and Teodoro PE (2016) Biplot analysis of phenotypic stability in upland cotton genotypes in Mato Grosso. *Genetics and Molecular Research* **15**, 1–10.

Farooq A, Shakeel A, Chattha WS, Khan TM, Azhar MT and Saeed A (2021) Genetic variability in cotton germplasm: predicting the agro physiological markers for high-temperature tolerance. *The Journal of Agricultural Science* **159**, 11–22.

Fok M (2006) Libéralisation, distorsion de concurrence et évolution technologique: portée et limites du succès du coton en Afrique Zone Franc. *Championing Agricultural Successes for Africa's Future: A Parliamentarians' Dialogue on NEPAD, Omerset West*, *South Africa*, 14–18 *May* 2006.

Gaetani M, Janicot S, Vrac M, Famien AM and Sultan B (2020) Robust assessment of the time of emergence of precipitation change in West Africa. *Scientific Reports* **10**, 1–10.

Gnofam N, Tozo K, Bonfoh B, Akantetou K, Kolani L and Ampouzouvi K (2014) Effets d'un déficit hydrique sur certains paramètres morphologiques, physiologiques et de rendement chez le cotonnier (Gossypium hirsutulm L. CV STAM129A) cultivé au Togo. *Agronomie Africaine* **26**, 113–125.

Guan K, Sultan B, Biasutti M, Baron C and Lobell DB (2017) Assessing climate adaptation options and uncertainties for cereal systems in West Africa. *Agricultural and Forest Meteorology* **232**, 291–305.

ITC (2011) Coton et changement climatique. Impacts et options de réduction et d'adaptation.

Khan A, Najeeb U, Wang L, Tan DKY, Yang G, Munsif F, Ali S and Hafeez A (2017) Planting density and sowing date strongly influence growth and lint yield of cotton crops. *Field Crops Research* **209**, 129–135.

Koller M (2016) Robustlmm: an R package for robust estimation of linear mixed-effects models. *Journal of Statistical Software* **75**, 1–24.

Kuznetsova A, Brockhoff PB and Christensen RHB (2017) lmerTest package: tests in linear mixed effects models. *Journal of Statistical Software* **82**, 1–26.

Lacape (1998) Analyse ecophysiologique de la reponse de varietes de cotonnier au deficit hydrique (PhD thesis). Montpellier, ENSA.

Lark RM, Ligowe IS, Thierfelder C, Magwero N, Namaona W, Njira K, Sandram I, Chimungu JG and Nalivata PC (2020) Longitudinal analysis of a long-term conservation agriculture experiment in Malawi and lessons for future experimental design. *Experimental Agriculture* **56**, 506–527.

Loison R, Audebert A, Chopart J, Debaeke P, Dessauw D, Gourlot J, Gozé E, Jean J and Gérardeaux E (2017) Sixty years of breeding in Cameroon improved fibre but not seed cotton yield. *Experimental Agriculture* **53**, 202–209.

Ndiaye M, Adam M, Kyky Ganyo K, Guissé A, Cissé N and Muller B (2019) Genotype-environment interaction: trade-offs between the agronomic performance and stability of dual-purpose Sorghum (Sorghum bicolor L. Moench) genotypes in Senegal. *Agronomy* **9**, 867.

Ndour A (2018) Estimation de la production cotonnière dans un contexte de changement climatique: cas du bassin cotonnier du Sénégal. Mémoire de Thèse. ED 2DS Université de Thiès. ED 2DS Université de Thiès.

Ndour A, Loison R, Gourlot JP, Seydi Ba K, Dieng A and Clouvel P (2017) Changement climatique et production cotonnière au Sénégal: concevoir autrement les stratégies de diffusion des variétés. *Biotechnology, Agronomy and Society and Environment* **21**, 22–35.

Oumarou P, Graveleau A, Memena O, Dessauw D and Klassou C (2014) Sélection cotonnière. Rapport annuel complet campagne 2013–2014.

Oumarou P, Oungvan M, Bayero M, Sigrist J-C, Klassou C, Cao T-V, Dessauw D, Gawrysiak G and Viot C (2019) 70 ans d'Amélioration Variétale du Coton au Cameroun.

PR-PICA (2019) ACTE DE LA DOUZIEME REUNION BILAN DU PR-PICA, 308.

Rusinamhodzi L, Murwira HK and Nyamangara J (2006) Cotton-cowpea intercropping and its N2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. *Plant and Soil* **287**, 327–336.

Sarr M, Traoré A, Kanfany G, Ly MO, Kane S and Gueye M (2021) Évolution de la production cotonnière au cours des onze dernières années au Sénégal: Études des contraintes liées à la production. *Journal of Applied Biosciences* **165**, 17078–17091.

Sekloka E, Lançon J, Batamoussi M and Thomas G (2015) La réduction de la croissance végétative à forte densité de semis comme stratégie d'adaptation variétale aux semis tardifs en culture cotonnière pluviale au. *Tropicultura* **33**, 299–308.

Sément G (1986) *Le Cotonnier en Afrique tropicale*. Paris: Maisonneuve et Larose-ACCT, 133 p. (Le Technicien d'agriculture tropicale, 5) ISBN: 2-7068-0922-1.

SODEFITEX (2019) Données statistiques agricoles de la campagne 2018–2019.

Stiller WN, Read JJ, Constable GA and Reid PE (2005) Selection for water use efficiency traits in a cotton breeding program: cultivar differences. *Crop Science* **45**, 1107–1113.

Sultan B, Bella-Medjo M, Berg A, Quirion P and Janicot S (2009) Multi-scales and multi-sites analyses of the role of rainfall in cotton yields in West Africa. *International Journal of Climatology* **30**, 58–71.

Taner B, Volcan S and Aydin U (2006) The effect of sowing date plant on cotton yield.pdf.

Traore B, van Wijk MT, Descheemaeker K, Corbeels M, Rufino MC and Giller KE (2014) Evaluation of climate adaptation options for Sudano-Sahelian cropping systems. *Field Crops Research* **156**, 63–75.

Tuttolomondo T, Virga G, Rossini F, Anastasi U, Licata M, Gresta F, La Bella S and Santonoceto C (2020) Effects of environment and sowing time on growth and yield of upland cotton (*Gossypium hirsutum* L.) cultivars in Sicily (Italy). *Plants* **9**, 1209.

UNCTAD and CNUCED (2016) COTON - Un profil de produit de base par INFOCOMM, 1–98.

Wang G, Li Y, Han Y, Wang Z, Yang B, Li X and Feng L (2020) Resource use efficiency in a cotton-wheat double-cropping system in the Yellow River Valley of China. *Experimental Agriculture* **56**, 422–439.

Wickham H (2011) The split-apply-combine strategy for data analysis. *Journal of Statistical Software* **40**, 1–29.

Wickham H (2016) *ggplot2: Elegant Graphics for Data Analysis*. New York: Springer-Verlag.