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

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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, Vélïngara 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 Vélïngara 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 late as possible in the late planting window). The eight cultivars were randomly assigned to sub plots within the main plots. The two factors (PD and cultivar) and three replicates. The two PDs were randomly assigned to the main plots using a complete block 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.

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:

\[ Y_{ijkl} = \mu + g_i + p_j + (gp)_{ij} + E_k + B(E)_{lk} + (gE)_{ik} + (pE)_{jk} + M(pE)_{jkl} + \epsilon_{ijkl} \]  

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;

\( \mu \) is the overall mean;

\( g_i \) is the effect of the \( i \)th genotype;

\( p_j \) 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

\( \epsilon_{ijkl} \) 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 ImerTest (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

<table>
<thead>
<tr>
<th>Research station</th>
<th>Coordinates</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Soil texture</th>
<th>Year</th>
<th>Planting date</th>
<th>Planting code</th>
<th>Environment code</th>
<th>$T_{\text{min}}$ (°C)</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>Rainfall (mm)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kédougou</td>
<td>12°39'N,</td>
<td>19.2</td>
<td>33.7</td>
<td>47</td>
<td>Silty clay loam</td>
<td>2018</td>
<td>June 28</td>
<td>P1</td>
<td>KG18P1</td>
<td>21.6 (2.9)$^c$</td>
<td>31.8 (2.4)$^c$</td>
<td>1096</td>
</tr>
<tr>
<td></td>
<td>12°7'W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2019</td>
<td>July 19</td>
<td>P2</td>
<td>KG18P2</td>
<td>20.3 (4.2)</td>
<td>32.2 (2.4)</td>
<td>984</td>
</tr>
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<tr>
<td>Vélingara</td>
<td>13°9'N,</td>
<td>27.9</td>
<td>48</td>
<td>24.6</td>
<td>Clay</td>
<td>2018</td>
<td>July 9</td>
<td>P1</td>
<td>VL18P1</td>
<td>22.8 (1.3)</td>
<td>31.0 (1.7)</td>
<td>801</td>
</tr>
<tr>
<td></td>
<td>14°2'W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2019</td>
<td>June 30</td>
<td>P2</td>
<td>VL18P2</td>
<td>22.0 (2.2)</td>
<td>30.9 (1.7)</td>
<td>656</td>
</tr>
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</tr>
<tr>
<td>Koussanar</td>
<td>13°55'N,</td>
<td>59.3</td>
<td>12.7</td>
<td>28.4</td>
<td>Sandy loam</td>
<td>2018</td>
<td>June 30</td>
<td>P1</td>
<td>KO18P1</td>
<td>23.2 (2.3)</td>
<td>33.2 (2.7)</td>
<td>412</td>
</tr>
<tr>
<td></td>
<td>14°3'W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2019</td>
<td>July 17</td>
<td>P2</td>
<td>KO18P2</td>
<td>21.9 (3.6)</td>
<td>33.6 (2.9)</td>
<td>382</td>
</tr>
<tr>
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</tbody>
</table>

KD, Kédougou; KO, Koussanar; VL, Vélingara.

*aClassification according to the USDA method based on data over the 0–30 cm horizon.

*bRainfall = total rainfall during the trial (from planting to harvest).

The standard deviation of the mean is indicated in parenthesis.
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, run off 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 (412, 382, 469, 349 and 656 mm, respectively). These temperatures are higher than

<table>
<thead>
<tr>
<th>Cultivar name</th>
<th>Origin</th>
<th>Traits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stam 129A</td>
<td>Togo</td>
<td>Reference, widely cultivated in Senegal, potential seed cotton yield of 3000 kg/ha, cycle of 120 days, cultivar released in 1998.</td>
</tr>
<tr>
<td>CS 50</td>
<td>Australia</td>
<td>Drought sensitive</td>
</tr>
<tr>
<td>TAMCOT CAMD-S-75-C</td>
<td>USA</td>
<td>Long vegetative phase and short reproductive phase</td>
</tr>
<tr>
<td>BUJA</td>
<td>Ivory Coast</td>
<td>Strong leaf reduction in drought conditions</td>
</tr>
<tr>
<td>ALLEN S1-106</td>
<td>Chad</td>
<td>Short vegetative phase and long reproductive phase</td>
</tr>
<tr>
<td>IRMA L484</td>
<td>Cameroon</td>
<td>Drought tolerant, cultivar released in 2006.</td>
</tr>
<tr>
<td>IRMA Q302</td>
<td>Cameroon</td>
<td>Drought tolerant, cultivar released in 2012.</td>
</tr>
<tr>
<td>SIOKRA L23</td>
<td>Australia</td>
<td>Drought tolerant and okra-leaf</td>
</tr>
</tbody>
</table>

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

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

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

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

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
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.

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).
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 3,368 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 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%.

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

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**Ethical standards.** Not applicable.

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