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Crop Science

ORIGINAL RESEARCH ARTICLE

Crop Breeding & Genetics

Growth, boll development, agronomic performance, and fiber quality of *Gossypium barbadense* L. in the southeastern U.S. Coastal Plain

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Abstract

Pima (*Gossypium barbadense* L.) cotton is currently grown commercially in the western United States and has exceptional fiber quality, which provides an economic value almost two times greater than Upland (*Gossypium hirsutum* L.) cotton. Due to limited experience with Pima production in the southeastern United States, our primary objective was to compare the growth, development, agronomic performance, and fiber quality of four Pima genotypes with a high-yielding high fiber quality commercial Upland cultivar under irrigated and dryland conditions at different planting dates. Lint yields of all Pima genotypes were ∼50% less and had lower lint percentages (38.0–42.4%) than the Upland genotype (45.7%); however, the Pima genotypes had consistently lower micronaire values and increased fiber strength, length, and uniformity. Although irrigation did not significantly impact agronomic and fiber quality performance, plants grown under supplemental irrigation developed 10% more bolls throughout the season, mostly occurring on monopodial branches and at mainstem nodal positions above 15. Bolls on Pima genotypes were 13–34% smaller than the Upland genotype and developed at more distal and higher nodal positions in the plant canopy. The highest net returns were found in 2019 at the early planting date, displaying the importance of timely planting of Pima genotypes when grown in the southeastern United States. Results suggest that irrigation may not be required for Pima production in the southeast, early planting is preferred to obtain maximum yields, and increasing lint percent, boll number, or earliness through breeding may improve Pima yields in the southeastern United States.

1 | INTRODUCTION

Currently, *Gossypium barbadense* L. (also known as Pima, Sea Island, Egyptian, or Extra-Long Staple) is commercially produced on approximately 103,000 ha in California, Arizona, New Mexico, and Texas, and comprises 3% of annual cotton production in the United States (USDA-NASS, 2018). Pima cotton genotypes produce extremely long, strong, and fine fibers compared with Upland genotypes, and the reported value of Pima fibers is usually double that of Upland cotton (*Gossypium hirsutum* L.) fibers, with Upland base quality averaging US\$2.38 kg^{-1} in October of 2021 and the base Pima averaging \$4.03 kg^{-1} (USDA-AMS, 2021). Since the early 1930s, the U.S. cotton belt has almost exclusively produced

Abbreviations: DAP, days after planting; DW, dry weight; LAI, leaf area index; RVR, reproductive to vegetative ratio.

Upland cotton. However, prior to the 1930s, Pima cotton was a large part of production in the southeastern Coastal Plain and was most often referred to as Sea Island cotton. Sea Island cotton was first introduced into the United States from the West Indies in 1790 by William Elliott on Hilton Head Island, SC and rapidly expanded in the early 1900s along the coastal regions of Georgia and South Carolina and into the northern region of Florida. During this early period, the southeastern United States was not only producing the later-maturing Sea Island cotton genotypes along the coast but was also planting the earlier-maturing Upland genotypes at more inland geographic regions. Historical records show that early breeding efforts with *G. barbadense* began in Florence, SC when J. S. Newman crossed Upland and Sea Island genotypes with the goal of developing new high-value Sea Island genotypes for the southeastern United States and was continued as part of the USDA-ARS initiative in 1935 to revitalize Sea Island cotton cultivation in the region (Culp & Harrell, 1974). Unfortunately, Sea Island cotton cultivation in the southeastern United States declined over the next few decades due to the invasion of the boll weevil (*Anthonmus grandis grandis Boh.*) into the region from Mexico in the early 1920s, and the Sea Island breeding program shifted direction to focus on breeding Pima fiber quality into Upland cotton (Campbell et al., 2011). The majority of the Sea Island genotypes grown during this era required a longer growing season to reach maturity compared with Upland cotton genotypes; this made Sea Island cotton more susceptible to boll damage from insect feeding, and thus less profitable. The final commercially produced Sea Island cotton in the southeastern United States was planted on Johns Island, SC in 1956 (Kovacik & Mason, 1985; Stephens, 1976). Today, most of the barriers that led to the shift away from Pima to Upland cotton production in the southeastern United States no longer exist, especially because the boll weevil has now been successfully eradicated from all cotton-producing states east of Texas.

Production strategies for Pima cotton are well established in the western United States and Texas, but management information is lacking in the southeast and will be needed if Pima is reintroduced into the region. Pima generally requires a longer growing season than Upland cotton to achieve maximum yields (Munk, 2001). Whereas optimum planting dates vary by location, planting Pima early (late March to early April) in soil conditions of 15–18 ˚C provided the best results in terms of yield based on research in Arizona (Silvertooth, 2001). In South Carolina and the southeastern Coastal Plain, cotton is generally planted between mid-April and the first week of June, but the optimal planting date for Upland cotton is usually between early- and mid-May (Jones et al., 2019). Pima grown in the western U.S. cotton belt is also regularly irrigated as the climate in this region is dryer and far less humid than the southeast. For example, Texas, one of the largest states in the cotton belt, only receives ∼50 cm of precipitation annually, whereas South Carolina experienced an average of 119 cm in 2019 (Raper et al., 2019; South Carolina State Climatology Office, 2019). Whereas irrigation may be slightly less crucial in the southeast, it can still be necessary to manage water stress. Water stress in Upland cotton can lead to reduced leaf area, reduced rate of photosynthesis, stunted plant growth, higher rates of square and boll abortion if it occurs during reproductive development, and eventually reduced yield (Pettigrew, 2004). Carmo-Silva et al. (2012) measured the canopy temperatures of four Pima cultivars under water-limited and well-watered conditions in Arizona and found that canopy temperature was significantly higher under water-limited conditions. This study also demonstrated a decrease in specific leaf area under water-limited conditions. Fiber length and strength can also be negatively impacted by water stress in the early and middle boll set periods (Farahani & Munk, 2012).

Core Ideas

- Early planting is desirable to maximize pima cotton production in the southeastern United States.
- Supplemental irrigation may not be required for southeastern U.S. pima cotton production.
- In comparison with Upland, more bolls did not translate to increased lint yield for pima cotton.

Leaf area and leaf thickness are two morphological traits of cotton that contribute to photosynthetic rate, transpiration rate, water deficit, productivity, and plant temperature. Thicker leaves generally are lower in temperature and exhibit high irradiance and a higher rate of photosynthesis than leaves with a larger leaf area (Pauli et al., 2017). Pima cotton leaves are broader and thinner than leaves of Upland cotton. This is due to a thicker palisade layer in Upland cotton, suggesting that Pima has a lower rate of photosynthesis than Upland (Wise et al., 2000). Wise et al. (2000) conducted a study comparing the leaves of Pima and Upland and found that Pima leaves were 39% larger than those of Upland and that the Upland leaves were 50% thicker than Pima leaves. Pauli et al. (2017) found similar results where Upland genotypes had thicker leaves than Pima, but they also found that Pima leaves were significantly thicker under irrigated conditions as opposed to dryland.

Previously, we compared the yield and fiber quality performance of 48 Pima genotypes with two popular Upland cultivars in the southeastern United States. On average, the Pima genotypes yielded 50% less than the Upland genotypes; however, most Pima genotypes had superior fiber quality (Holladay et al., 2021). Whereas this study helped identify several promising Pima genotypes for use in breeding studies aimed at developing new Pima breeding lines with southeastern United States adaptation, more information on plant physiology and management practices are needed to determine the feasibility of Pima cotton production in the southeastern United States. Management practices for the successful production of Upland cotton in the southeastern United States are already well-established and implemented in the region. Determining the optimal management practices for Pima cotton in the southeastern United States is essential for reintroducing it into the region. In this study, our primary objective was to compare the growth, development, yield performance, and fiber quality of four promising Pima genotypes with a high-yielding, high-fiber quality commercial Upland cultivar. Secondary objectives were to determine the impact of planting date and supplemental irrigation on Pima cotton production.

2 | MATERIALS AND METHODS

Field studies were conducted in 2018 and 2019 at the Clemson University Pee Dee Research and Education Center in Florence, SC on a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic Aquic Paleudults). Five cotton genotypes were sown at three planting dates (early, normal, and late) and grown under irrigated and dryland conditions each year. Three commercial Pima genotypes (‘DP 348RF’, ‘PHY 881RF’, and ‘PHY 841RF’), which are currently planted on the majority of the Pima cotton acreage in the United States (USDA-AMS, 2019), were chosen to provide high-yielding, high-fiber quality comparisons with the other two genotypes selected. Another Pima genotype, P 62 (PI 542773), was selected based upon prior, preliminary data collected at the same location (Holladay et al., 2021). An Upland commercial cultivar, ‘DP 1646B2XF’, was included as a standard for southeastern U.S. cotton production. DP 1646B2XF has consistently produced high yields and high fiber quality in southeastern U.S. official variety trials (Jones et al., 2018) and is currently the most widely planted cultivar in the region (USDA-AMS, 2018). The five cotton genotypes were planted at a seeding rate of 13 seed m^{-2} on 30 Apr. 2018 and 30 Apr. 2019 (early), on 14 May 2018 and 13 May 2019 (normal), and on 30 May 2018 and 29 May 2019 (late) using a JD 7200 planter (John Deere) equipped with individual cone-planter units (Almaco).

The experimental design was a four replicate randomized split-split plot with irrigation as the main plot, planting date as the sub-plot, and genotypes as the sub-sub plot. The study consisted of 120 2-row plots that were 96.5 cm apart and 12.2 m long. Irrigated plots received 2.54 cm of water on 9 July 2018 and 16 July 2018 with an overhead lateral system equipped with low-pressure drop nozzles. Irrigated plots received 2.00 cm for the initial application on 29 May 2019 and 2.54 cm on 2 July 2019 and 8 Aug. 2019. Dryland plots did not receive any supplemental irrigation in either year. At planting, 0.84 kg ha^{-1} aldicarb [2-methyl-2-(methylthio) propionaldehyde O-(methylcarbamoyl) oxime] was applied in-furrow to aid with early season insect and nematode control. Later, insecticide applications of 0.04 kg ha^{-1} of Lambda-cyhalothrin were made as needed to control *Helicoverpa zea*, *Heliothis virescens*, *Euschistus servus*, *Nezara viridula*, and *Halyomorpha halys* species. At planting, a tank mixture of 0.43 kg ha^{-1} of fomesafen and 1.10 kg ha^{-1} of pendimethalin was soil applied pre-emergence to all plots. Post-emergence weed control was accomplished using post-directed applications of 2.30 kg ha^{-1} of monosodium acid methanearsonate and 0.85 kg ha^{-1} of prometryn. All herbicide applications were applied uniformly at the appropriate time of crop development for each planting date, and hand-weeding was used when necessary to maintain weed-free plots. Depending on planting dates, 90 kg N ha^{-1} (as a urea ammonium sulfate solution) was applied beside each row at the pinhead to matchhead square stage of development.

Above ground dry matter harvests were collected from 0.5 m^2 of row from each of the late-April planted plots on 9 July and 24 July in both 2018 and 2019. When a single harvest required more than 1 d for completion of the whole experiment, only complete replications were harvested on any single day. The average day of the sampling dates for each harvest is presented. Plant sample harvest varied from 6 to 12 plants m^{-2} depending on the genotype, and the aboveground portions of each sample were separated into leaves, stems (branches and petioles also), squares (floral buds), and bolls. A leaf subsample consisting of the leaves from one representative plant was used for leaf area measurement. Leaf area index (LAI) was determined using a LI-3100 leaf area meter (LI-COR), and plant height, number of mainstem nodes, and monopodia numbers were recorded. Samples were dried in a forced-air oven at 70 ˚C for 48 h, and the dry weights were recorded. Traditional plant mapping was also performed at the end of each year to determine boll location, number of nodes and bolls, plant height, and boll retention (Jones et al., 1996). Plants from 0.5 m^2 of row from each of the 120 sub-sub plots were evaluated just prior to harvest each year, and plant height, node of the first fruiting branch, total number of nodes, and the location of each boll on a fruiting branch were recorded.

All plots were harvested with a two-row spindle-picker (Case IH 1822) modified with an onboard weigh system for small research plots. In 2018, the late-April planted plots were harvested on 9 Oct. or 162 d after planting (DAP), and the mid- and late-May planted plots were harvested on 25 Oct. 2018 or 163 and 148 DAP. In 2019, the late-April and mid-May planted plots were harvested on 1 Oct. 2019 or 154 and 140 DAP, and the late-May planted plots were harvested on 5 Nov. 2019 or 160 DAP. In both years, a 25-boll sample was collected from each plot for boll weight determination, and two 250–350 g subsamples of cotton were collected for ginning and fiber quality analysis. One of the two subsamples of seed cotton was ginned using a 10-saw gin (Continental Gin), whereas the other was ginned in Arizona at Olvey and Associates on a roller gin (Lummus); fiber quality data from the roller gin was not included in this portion of the study, but instead was used in a companion study (Holladay et. al, 2021). The gin turnout data from the saw gin were then used to calculate the lint yield on a kg ha^{-1} basis. After ginning, approximately 30 g of lint was obtained for each plot and sent to the Texas Tech University Fiber and Biopolymer Research Institute in Lubbock, TX to be evaluated on a high-volume instrument each year. Fiber properties determined from the high-volume instrument analysis included fiber length, fiber strength, micronaire, uniformity, and elongation.

Net returns were determined from Cotton Incorporated's Loan Calculator (Cotton Incorporated, 2019), where the value of the lint (including the premiums and discounts for fiber quality) and value of the seed were combined, and the cost of ginning and harvesting were subtracted. In both years of the study, the Pima genotypes were compared with the Upland check by using the Pima base loan rate of \$2.09 kg^{-1} and the Upland base loan rate of \$1.15 kg^{-1} (which were the loan rates in 2019) and by using the Upland criteria for premiums and discounts.

All data were analyzed using an ANOVA in JMP Pro 14.3 software (SAS Institute) using a mixed model. Random effects were block (nested within year), block (nested within year) × irrigation, and block (nested within year) × irrigation × planting date and block (nested within year) × irrigation × planting date × genotype. The fixed effects consisted of a full factorial of year, irrigation, planting date, and genotype. All means were separated using Fisher's protected LSD at the .05 level of probability.

3 | RESULTS AND DISCUSSION

No differences in lint yield were found between irrigated or dryland treatments and no significant interactions were detected with irrigation, so lint yield data was combined over irrigation treatments (Tables 1 and 2). This lack of response to irrigation may suggest that irrigation is less crucial for Pima production in the southeastern United States than it is in the western United States. In both years of the study, the Upland check DP 1646B2XF consistently produced ~60% more lint yield than the four Pima genotypes; however, significant genotype × year, planting date × year, and planting date × genotype interactions were detected (Tables 1 and 2).

The Pee Dee area of South Carolina experienced very different environmental conditions between 2018 and 2019, with two major tropical storms occurring prior to harvest in 2018 and more optimal harvest conditions existing in 2019 (Table 3). Hurricane Florence impacted the study location in Florence, SC on September 14–16, followed by Tropical Storm Michael on 10 Oct. 2018 and 11 Oct. 2018. In total, the storms provided 35 cm of rainfall, which led to difficult harvest conditions. The unfavorable harvest conditions in 2018 associated with these two major storms was a possible factor that led to a reduction of the lint yield of DP 1646B2XF by 21% compared with 2019, but with only limited impact on the lower yielding Pima genotypes. The lint yield of DP 1646B2XF increased from 1,161 to 1,473 kg ha^{-1} in 2018 and 2019, respectively, whereas the lint yield of the four Pima genotypes remained in the 459–587 kg ha^{-1} range.

Lint yield response to planting date was also different in 2018 and 2019 and varied significantly depending on the genotype planted (Tables 1 and 2). In 2018, few differences were found in lint yield among the three planting dates and there appeared to be no advantage or disadvantage to early or late planting. However, in 2019, the early planting date produced 20% more lint yield than the normal planting date and 14% more lint yield than the late planting date (Table 2). Because late-planted plots had mature open bolls during the timing of the tropical storms in 2018, any advantages gained from planting Pima genotypes early may have been negated with the weathering and exposure of the open lint to rainfall and high winds. When averaged over years, delayed plantings appeared to decrease lint yield numerically by 7–9% for each 2-wk interval of delay throughout the season (Table 2). A significant planting date × genotype interaction was also detected for lint yield, with the late planting resulting in a 14–19% decrease in lint yield of DP 1646B2XF and a 14–25% decrease in lint yield of P 62 when compared with the early and normal planting dates, respectively (Table 2). Lint yield of PHY 881RF and DP 348RF was not affected by planting date; however, PHY 841RF produced lower lint yield with the normal planting date (Table 2).

Gin turnout was increased with irrigation in 2018 but not in 2019 (Table 4). Gin turnout was not affected by planting date in 2018, but the late planting reduced gin turnout in 2019 when compared with earlier plantings. In both years of the study, DP 1646B2XF had higher gin turnout than the Pima genotypes, averaging 45.4% in 2018 and 45.9% in 2019 compared with the Pima genotypes, which ranged from 38.4 to 42.9% in 2018 and 37.5 to 41.8% in 2019. The commercial Pima genotypes PHY 841RF and PHY 881RF had a higher gin turnout than the other two Pima genotypes evaluated in this study.

With the exception of micronaire, plants grown in 2018 had decreased fiber quality compared with 2019 (Table 4). Fibers were 3% longer, 9% stronger, and 2% more uniform in the 2019 growing season. When averaged over years, PHY 881RF and PHY 841RF produced longer fibers (33.9 and 33.7 mm, respectively) than the other two Pima genotypes (33.1 and 32.2 mm) and the Upland genotype (30.7 mm). There was

TABLE 1 Level of significance for lint yield, lint percent, fiber length, fiber strength, fiber uniformity, fiber elongation, micronaire, and loan value for five cotton genotypes grown at the PDREC in Florence, SC, in 2018 and 2019

Source of variation	df	Lint yield	Gin turnout	Fiber length	Fiber strength	Fiber uniformity	Fiber elongation	Micronaire	Loan value
Year (Y)	1	0.0934	0.3653	0.0002*	<.0001*	0.0007*	<.0001*	0.0904	0.1356
Irrigation (Irr)	1	0.8649	0.0017*	0.3410	0.4554	0.9260	0.3839	0.0902	0.8552
Irr × Y	2	0.8400	0.0022*	0.4898	0.4839	0.2184	0.6912	0.6789	0.7613
Planting date (PD)	2	0.1204	0.0122*	0.9928	0.0007*	0.1310	0.6261	<.0001*	0.2733
PD × Y	2	0.0165*	0.0073*	0.0048*	0.0018*	0.1905	<.0001*	<.0001*	0.0060*
Irr × PD	2	0.1080	0.6525	0.3184	0.0373*	0.1142	0.2697	0.1931	0.1003
Irr × Y × PD	4	0.1088	0.5024	0.4088	0.2582	0.2404	0.2129	0.0490*	0.1212
Genotype (G)	4	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
G × Y	4	<.0001*	0.0908	<.0001*	<.0001*	<.0001*	0.0127*	<.0001*	0.0615
Irr × G	4	0.8000	0.1667	0.6763	0.9565	0.5230	0.4985	0.8963	0.6797
Irr × G × Y	8	0.8779	0.5267	0.7388	0.9653	0.5069	0.3923	0.5564	0.7797
PD × G	8	0.0012*	0.1316	0.7837	0.9624	0.4992	0.4919	0.6677	0.0410*
PD × G × Y	8	0.1633	0.3387	0.5806	0.8789	0.0347*	0.5722	0.5853	0.0787
Irr × PD × G	8	0.5111	0.9922	0.9048	0.8429	0.5715	0.6481	0.4997	0.6324
Irr × PD × G × Y	8	0.1839	0.2860	0.7770	0.6458	0.3697	0.9212	0.7267	0.6044

Note. Error df = 144.

*Significant at the .05 probability level.

TABLE 2 Lint yield of five cotton genotypes in response to planting date when grown at the PDREC in Florence, SC, in 2018 and 2019

Genotype (G)	Planting date (PD)											
	Early			Normal			Late			G × Y mean		G
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
	kg ha^{-1}											
DP 1646B2XF	1,297	1,563	1,430	1,235	1,480	1,358	950	1,377	1,164	1,161	1,473	1,317
PHY 881RF	457	682	570	691	494	593	531	583	557	560	587	574
PHY 841RF	471	639	555	550	376	463	553	634	594	525	550	538
P 62	529	663	596	564	480	522	407	489	448	500	544	522
DP 348RF	414	676	545	485	541	513	478	541	510	459	586	523
PD Mean	634	845	*740*	705	674	*690*	584	725	*655*	641	748	
LSD (.05)	PD = NS		G = 73	PD × G = 126			PD Y = 120		G × Y = 31		PD × G × Y = NS	

Note. Means averaged over two irrigation treatments.

a significant genotype × year interaction detected for fiber length, with PHY 881RF, PHY 841RF, and DP 348RF having longer fibers in 2019 compared with 2018 and with DP 1646B2XF having shorter fibers in 2019 compared with 2018 (Table 4). The Pima accession, P 62, averaged 32.2-mm fiber length and did not show a significant difference in fiber length between years. Planting date and irrigation did not affect fiber length in either year of this study; however, there was a significant planting date × year interaction found where late-planted cotton produced shorter fibers in 2018 and longer fibers in 2019 (Table 4). The minimum fiber length requirement for Pima cotton in the United States is 34.9 mm to receive the premium for fiber quality (USDA-FSA, 2019). In this study, only one Pima genotype (PHY 881RF) exceeded the requirement (despite all the Pima genotypes having longer fibers than DP 1646B2XF) with a fiber length of 35.0 mm in 2019 only. When a one-sample t-test was performed, PHY 841RF was also not significantly different ($p = .0931$) from the minimum requirement with a fiber length of 34.6 mm in 2019, compared with all other genotypes, which differed significantly from the minimum requirement for fiber length ($p < .0001$) in both years at the .05 level of probability.

Genotypes in 2019 had stronger fibers than in 2018, with the trial mean increasing from 367 kN m kg^{-1} to 401 kN

TABLE 3 Monthly weather summary for 2018 and 2019 at the PDREC in Florence, SC

Month	Precipitation 2018	Precipitation 2019	Thermal units[a] 2018	Thermal units[a] 2019
	——cm——			
Apr.	11.0	9.6	0	0
May	13.0	3.5	5.5	7.5
June	11.7	4.9	10.3	8.1
July	11.5	15.4	10.1	11.6
Aug.	2.2	9.6	9.7	10.1
Sept.	30.6	9.2	10.7	7.7
Oct.	15.0	6.5	2.7	4.8
Nov.	12.7	6.3	0	0

[a]([maximum temperature ± minimum temperature] % 2), 15.5 °C.

m kg^{-1} (Table 4). All Pima genotypes had stronger fibers (50–76 kN m kg^{-1} stronger in 2018 and 76–150 kN m kg^{-1} stronger in 2019) than the Upland check in both years of the study. DP 348RF had the strongest fibers both years (Table 4). There was a significant genotype × year interaction for fiber strength, where only DP 348RF, PHY 841RF, and PHY 881RF had stronger fibers in 2019 compared with 2018. There were no differences in fiber strength among the three planting dates in 2019, but there was a difference in fiber strength in 2018 with the late planting date having stronger fibers than the early and normal planting dates. The late planting date effect in 2018 was possibly due to these late-planted plots having closed bolls at the time of the storms so that fiber was not exposed to weathering. Irrigation did not affect fiber strength in either year of the study (Table 4). Pima cotton grown in the United States requires a minimum strength reading of 363 kN m kg^{-1} to avoid discounted fiber quality (USDA-FSA, 2019). In both years, all the Pima genotypes exceeded the minimum requirement, ranging from 365 to 391 kN m kg^{-1} in 2018 and from 374 to 448 kN m kg^{-1} in 2019. However, when a one-sample t-test was performed to test the observed fiber strength to the minimum fiber strength requirement, only two Pima genotypes (DP 348RF and PHY 881RF) had fiber strengths that were significantly higher ($p < .05$) than 363 kN m kg^{-1} in 2018. In 2019, all four Pima genotypes had significantly higher ($p < .05$) fiber strength than the minimum requirement.

Higher micronaire values (4.2 in 2018 and 4.7 in 2019) were found for DP 1646B2XF compared with the Pima genotypes in both years of the study, indicating that the Pima genotypes produced finer fibers than the Upland check DP 1646B2XF (Table 4). A significant genotype × year interaction was detected for micronaire, with P 62 and DP 1646B2XF having higher micronaire values in 2019 than in 2018 (Table 4). However, there were no differences in micronaire between years (Table 1). When averaged over years, there appeared to be a slight decrease in micronaire as planting was delayed; however, no significant differences were found between planting dates in 2018. In 2019, the early and normal planting dates had higher micronaire values than the late

TABLE 4 Gin turnout and fiber quality means for five cotton genotypes grown at the PDREC in Florence, SC, under two irrigation treatments and three planting dates in 2018 and 2019

Parameter	Gin turnout 2018	Gin turnout 2019	Fiber length 2018	Fiber length 2019	Fiber strength 2018	Fiber strength 2019	Fiber uniformity 2018	Fiber uniformity 2019	Micronaire 2018	Micronaire 2019
	——%——		——mm——		—kN m kg^{-1}—		——%——			
Irrigation										
Irrigated	42.4	41.4	32.2	33.1	365	402	84.9	85.3	4.1	4.0
Dryland	41.4	41.3	32.4	33.1	369	402	85.5	85.2	4.2	4.1
LSD (.05)	.3	NS	NS	NS	NS	NS	NS	NS	NS	NS
Planting date										
Early	41.8	41.7	32.3	33.1	345	401	84.9	85.2	4.0	4.2
Normal	42.0	42	32.6	32.7	371	400	85.5	85.2	3.9	4.1
Late	42.0	40.4	32.0	33.5	385	404	85.2	85.4	3.9	3.7
LSD (.05)	NS	1.3	.7	.7	16	NS	NS	NS	NS	.2
Genotype										
DP1646B2XF	45.4	45.9	31.3	30.1	315	298	83.2	83.7	4.2	4.7
PHY 881RF	42.3	41.6	32.8	35.0	387	445	84.1	86.9	3.8	3.8
PHY 841RF	42.9	41.8	32.7	34.6	377	444	84.2	86.4	3.9	3.8
P 62	38.4	37.5	32.2	32.2	365	374	83.8	82.9	3.8	4.1
DP 348RF	40.6	39.9	32.5	33.6	391	448	84.4	86.4	3.7	3.7
LSD (.05)	.7	1.0	.7	.6	29	12	.8	.7	.2	.2

TABLE 5 Plant height, total nodes, and boll positions on sympodial branch at the end of the growing season of cotton grown at the PDREC in Florence, SC under two irrigation treatments and three planting dates in 2018 and 2019

					Horizontal sympodial boll position							
	Plant height		**Total nodes**		**1**		**2**		**3**		**4+**	
	cm plant^{-1}		**Nodes plant^{-1}**		**–Bolls m^{-2}–**							
Parameter	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**	**2018**	**2019**
Irrigation												
Irrigated	84	86	18	20	61	49	26	22	7	8	1	1
Dryland	78	83	18	19	55	47	21	21	5	7	2	1
LSD (.05)	7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Planting date												
Early	76	88	19	20	61	56	29	22	10	9	3	2
Normal	80	89	17	20	65	48	24	25	4	10	1	2
Late	87	75	18	19	47	41	17	17	4	5	1	1
LSD (.05)	7	13	1	1	13	7	5	3	5	4	2	1
Genotype												
DP 1646B2XF	84	87	18	18	55	52	19	18	4	3	1	1
PHY 881RF	76	82	18	20	57	47	22	23	4	9	1	2
PHY 841RF	79	82	18	20	58	45	21	24	6	9	2	1
P62	85	87	19	20	53	46	29	23	11	11	4	3
DP 348RF	80	83	18	19	66	50	26	20	5	7	1	1
LSD (.05)	4	5	1	1	9	NS	7	5	5	4	2	2

planting date (Table 4). Irrigation had no effect on micronaire in either year of the study (Table 1). The minimum micronaire requirement to avoid discounted fiber quality is 3.5 in the United States (USDA-FSA, 2019). All Pima genotypes exceeded the requirement in both years of the study with values ranging from 3.7 to 3.9 in 2018 and from 3.7 to 4.1 in 2019. A one-sample t-test was performed to test the micronaire of each Pima genotype to the minimum requirement of 3.5, and in 2018 all four Pima genotypes were significantly higher ($p < .0001$) than 3.5. In 2019, the micronaire values of P 62, PHY 881RF, and PHY 841RF were all significantly higher ($p \leq .0002$) than 3.5, and DP 348RF was also significantly higher than 3.5 with a p value of .0395.

Fiber uniformity was higher in 2019 than in 2018 (Table 1) with a trial mean of 85.3% in 2019 and 83.9% in 2018. With the exception of P 62, the Pima genotypes had more uniform fibers than the Upland check in both years of the study. DP 348RF had the most uniform fibers in 2018 and PHY 881RF had the most uniform fibers in 2019 (Table 4). Pima genotypes ranged in uniformity from 83.8 to 84.4% in 2018 and from 82.9 to 86.9% in 2019, whereas DP 1646B2XF had 83.2% in 2018 and 83.7% in 2019. Irrigation and planting date had no effect on fiber uniformity in either year of the study (Table 1).

Irrigated genotypes were 8% taller in 2018, but no differences in plant height occurred in 2019 (Table 5). Averaged over years, irrigated genotypes were about 3–6 cm taller than dryland genotypes (Table 5). The Pima genotype P 62 was the tallest of all the Pima genotypes over both years but was not different than DP 1646B2XF in either year. In 2018, the late planting date produced the tallest plants, and in 2019 the early and normal planting dates produced the tallest plants.

Results from dry matter partitioning and leaf area measurements (Table 6) showed the commercial Pima genotype DP 348RF produced more leaves at late-bloom, with higher LAI and greater leaf dry weight (DW) at 85 DAP. These differences were not seen 15 d earlier at early bloom as there were no differences found in LAI and leaf DW among the five genotypes at 70 DAP. Overall, significant differences for dry matter parameters among genotypes were mostly seen from samples collected 85 DAP, with the exception of stem DW, which showed DP 1646B2XF had higher stem DW than the Pima genotypes at 70 DAP (Table 6).

With the exception of the Pima genotype P 62, the Upland check DP 1646B2XF also had more squares at early bloom and more bolls at late bloom compared with the commercial Pima genotypes (Table 7). This resulted in higher reproductive DW (148 g m^{-2}) and a greater reproductive to vegetative ratio (RVR = 0.49) from samples collected at 85 DAP, indicating that Pima genotypes appear to be slower transitioning from vegetative development into boll development.

TABLE 6 Vegetative growth characteristics measured at 70 (early bloom) and 85 (late-bloom) days after planting (DAP) in 2018 and 2019 of five cotton genotypes grown at the PDREC in Florence, SC

	Total DW		Vegetative DW		Stem DW		Leaf DW		Leaf area index	
Genotype (G)	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**
	g m^{-2}				g 0.5 m^{-2}				$\text{m}^2\ \text{m}^{-2}$	
DP 1646B2XF	270	475	243	327	69	97	53	67	1.8	2.4
PHY 881RF	242	374	219	305	51	81	58	71	2.0	2.3
PHY 841RF	247	400	215	320	51	89	56	71	1.9	2.5
P 62	252	438	223	339	57	98	55	72	1.8	2.5
DP 348RF	251	484	226	398	55	114	58	85	2.1	3.0
LSD (.05)	NS	76	NS	58	17	17	NS	14	NS	.5

Note. Dry matter partitioning samples were collected from the early planting only and means are averaged over years and irrigation treatments. DW, dry weight.

TABLE 7 Reproductive growth measured at 70 (early bloom) and 85 (late-bloom) days after planting (DAP) in 2018 and 2019 and end of season boll weights of five cotton genotypes grown at the PDREC in Florence, SC

	Number of squares m^{-2}		Number of bolls m^{-2}		Reproductive DW		RVR		Boll size
Genotype (G)	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**70 DAP**	**85 DAP**	**At harvest**
					g m^{-2}		g g^{-1}		g boll^{-1}
DP 1646B2XF	41	29	5	20	27	148	0.11	0.49	4.5
PHY 881RF	31	31	3	12	23	69	0.10	0.23	3.2
PHY 841RF	32	25	3	14	33	80	0.18	0.25	3.2
P 62	45	47	5	23	29	98	0.13	0.31	4.0
DP 348RF	26	33	3	15	26	86	0.12	0.22	3.0
LSD (.05)	12	13	NS	5	NS	30	NS	.1	.2

Note. Dry matter partitioning samples were collected from the early planting only and means are averaged over years and irrigation treatments. End of season individual boll weights were measured in 2019 at harvest time and are averaged over irrigation treatments and planting dates. DW, dry weight; RVR, reproductive to vegetative ratio.

Reproductive DW averaged 69–98 g m^{-2}, and RVR averaged 0.22–0.31 at 85 DAP for the Pima genotypes in this study (Table 7). The increased reproductive DW in DP 1646B2XF is likely the result of larger boll size (Table 7). Unrah et al. (1994) found similar results when comparing the RVR from an Upland cultivar with a Pima genotype in Arizona with the Upland having a higher RVR (0.83) than Pima (0.70). DP 1646B2XF and Pima accession P 62 had more bolls than the commercial Pima genotypes at 85 DAP (Table 7), but at the end of the season, DP 1646B2XF had the lowest number of bolls when averaged over years (Table 8). Thus, Pima genotypes appear to mature and produce most of their bolls later in the season compared with Upland genotypes, which is consistent with previous research that demonstrates Pima cotton requiring a longer growing season than Upland cotton (Munk, 2001). Witt et al. (2020) had similar results where the Pima genotypes produced more bolls during mid- and late-season.

Results from end of season plant mapping showed the early and normal planting dates produced more bolls (104 and 102 bolls m^{-2}, respectively) than the late planting date (84 bolls m^{-2}). Irrigation had a significant effect on boll number where irrigated plots averaged 102 bolls m^{-2} and dryland plots averaged 92 bolls m^{-2} (Table 8). Supplemental irrigation increased boll number by 10% by the end of the growing season, with increases mostly occurring on monopodial branches and at mainstem nodal positions above node 15 (Table 8). However, this increase in boll number due to irrigation did not translate to increased lint yield. The Pima genotypes P 62, DP 348RF, and PHY 881RF produced more bolls than DP 1646B2XF (Table 8). However, DP 1646B2X produced larger bolls, which likely explains the higher lint yield of DP 1646B2XF (Table 7). This is consistent with results from a previous study in Arizona where the Upland cultivar was more efficient at partitioning its total reproductive dry matter into lint dry matter (23% lint) than the Pima genotype (14% lint) (Unrah et al., 1994). Bolls on the Pima genotypes were approximately 23–34% smaller than DP 1646B2XF and developed at more distal and higher nodal positions in the plant canopy (Table 8). DP 16464B2XF and the Pima accession P 62 developed the majority of their bolls lower on the plant, between nodes six and ten, whereas the other three Pima

TABLE 8 Total boll number, boll location on the mainstem, and number of monopodial bolls produced by cotton grown at the PDREC in Florence, SC, in 2018 and 2019

Parameter	Total bolls	Mainstem nodes 1–5	Mainstem nodes 6–10	Mainstem nodes 11–15	Mainstem nodes 16–27	Monopodial bolls
	Bolls m^{-2}					
Year						
2018	98	2	46	38	8	4
2019	96	0	32	40	12	12
LSD (.05)	NS	1	4	NS	NS	2
Irrigation						
Irrigated	102	2	40	40	12	8
Dryland	92	2	38	38	8	6
LSD (.05)	8	NS	NS	NS	1	1
Planting date						
Early	104	2	46	40	12	4
Normal	102	0	42	42	10	8
Late	84	0	30	36	6	10
LSD (.05)	8	1	6	4	2	NS
Genotype						
DP 1646B2XF	84	2	44	26	4	8
PHY 881RF	100	0	36	44	12	8
PHY 841RF	94	0	34	44	12	4
P 62	106	2	44	38	10	12
DP 348RF	96	0	38	44	10	4
LSD (0.05)	12	1	6	6	4	4

Note. Means for irrigation, planting date, and genotype treatments averaged over years.

TABLE 9 Loan value ($ ha^{-1}) of five cotton genotypes in early, normal, and late planting dates when grown at the PDREC in Florence, SC, in 2018 and 2019

	Early			Normal			Late			G × Y mean		
Genotype (G)	**2018**	**2019**	**Mean**	**2018**	**2019**	**Mean**	**2018**	**2019**	**Mean**	**2018**	**2019**	**G mean**
DP1646B2XF	1,226	1,470	1,348	1,164	1,401	1,283	996	1,297	1,147	1,127	1,389	1,258
PHY 881RF	885	1,327	1,106	1,339	961	1,150	1,028	1,127	1,078	1,085	1,139	1,112
PHY 841RF	914	1,243	1,079	1,067	731	899	1,072	1,228	1,150	1,018	1,132	1,075
P 62	974	1,273	1,124	1,038	922	980	771	934	853	929	1,067	998
DP 348RF	771	1,310	1,041	899	1,048	974	887	1,043	965	853	1,043	948
PD × Y Mean	954	1,325		1,101	998		951	1,126		1,002	2,885	
LSD (0.05)	PD = NS		PD × Y = 198		G = 119		G × Y = NS (.06)		PD G = 183		PD × G × Y = NS (.07)	

Note. Means averaged over irrigation treatments and planting dates.

genotypes developed the majority of their bolls between nodes 11 and 15 (Table 8). In both 2018 and 2019, the early and normal planting dates produced more first-position bolls than the late planting date. Irrigation had no impact on horizontal sympodial boll position. In 2018, DP 348RF produced the most bolls in the first sympodial position (66 bolls m^{-2}), and in 2019, there were no differences between genotype and number of first position bolls (Table 5).

Net returns of the Upland check DP 1646B2XF were higher than the four Pima genotypes early and normal planting dates, except PHY 881RF, which had a loan value of $1,339 ha^{-1} for the normal planting date compared with $1,164 ha^{-1} for

DP 1646B2XF (Table 9). No differences in net returns were found among the five genotypes in 2018 when cotton was planted late, and loan values were reduced to \$951 ha^{-1}. The highest net returns were found in 2019 for the early planting date (\$1,325 ha^{-1}). This demonstrates the importance of early planting for Pima cotton production in the southeastern United States. With the exception of PHY 841RF, which averaged \$1,228 ha^{-1} for the late planting date in 2019, net returns of all Pima genotypes planting at the normal and late dates were lower than DP 1646B2XF (Table 9).

4 | CONCLUSIONS

Environmental conditions varied greatly between 2018 and 2019; however, the Upland check DP 1646B2XF produced lint yields 52–63% higher than the Pima genotypes. The Pima genotypes also had lower gin turnout (38.0–42.4%) than the Upland check genotype (45.7%), but consistently produced lower micronaire, increased fiber strength, increased fiber length, and improved fiber uniformity compared with DP 1646B2XF. The large difference in yield between the Pima genotypes and the Upland check DP 1646B2XF was not surprising as DP 1646B2XF has better adaptation to the southeastern Coastal Plains, accounting for approximately 36% of the cotton acreage planted in the southeastern United States (USDA-AMS, 2019). As expected, this study demonstrates that Pima cotton produced in the southeastern United States can produce fiber quality superior to Upland cotton. In addition, the Pima genotypes evaluated in this study also demonstrated the ability to meet or exceed the minimum requirements for Pima fiber strength and micronaire to avoid discounted fiber quality. Unfortunately, only two of the Pima genotypes (PHY 881RF and PHY 841RF) had fiber lengths equivalent to the minimum Pima requirement in 2019 only. This finding is likely a consequence of the lack of adaptation for these Pima genotypes to the southeastern United States. However, when a greater number of Pima genotypes were surveyed, there were several other genotypes that achieved Pima fiber lengths (Holladay et al., 2021).

Irrigation had no significant impact on lint yield, fiber quality, or loan value in either year, which suggests that supplemental irrigation may not be necessary for successful Pima production in the southeastern United States. However, this study shows that planting date can impact production. The late planting date resulted in a 14–19% decrease in lint yield of DP 1646B2XF and a 14–25% decrease in lint yield of P 62 when compared with the early and normal planting dates. Reduced fiber lengths were also found for the late planting date in 2018 and gin turnout in 2019. As planting date was delayed, fiber strength (2018) and micronaire (2019) also decreased. The highest net returns were found in 2019 for all five genotypes when planted early (\$1,325 ha^{-1}), and the highest lint yields for all five genotypes were observed with the early planting date in 2019 (845 kg ha^{-1}), demonstrating the importance of early planting for Pima production in the southeastern United States.

Although yields were low for the Pima genotypes compared with the Upland check DP 1646B2XF, this study was an informative initial step in the direction of reintroducing Pima production into the southeastern United States. Plant mapping and dry matter partitioning data revealed that, although Pima cotton produced a greater number of bolls than Upland cotton, a higher number of bolls did not translate to increased lint yield. Although this could be a result of later maturity associated with Pima cotton, this finding may serve as a target for improvement in Pima production in the southeastern United States. In general, more research is needed to determine if Pima cotton production can be economically feasible in the southeastern United States.

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AUTHOR CONTRIBUTIONS

Sarah K. Holladay: Data curation; Formal analysis; Investigation; Validation; Visualization; Writing – original draft; Writing – review & editing. william bridges: Formal analysis; Writing – review & editing. Michael Jones: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing. Todd Campbell: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing.

CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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