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Crop Science

ORIGINAL RESEARCH ARTICLE

Crop Breeding & Genetics

Yield performance and fiber quality of Pima cotton grown in the southeast United States

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Abstract

Commercial production of Pima cotton (*Gossypium barbadense* L.) in the United States is currently limited to the western United States and West Texas. Before the 1930s, Pima cotton was produced in coastal regions of the southeast United States. However, in an effort to escape yield and economic losses caused by the boll weevil, which invaded the United States in the 1920s, production of long-season Pima cotton was eliminated and shifted to shorter-season upland cotton (*Gossypium hirsutum* L.). Today, the value of Pima cotton fiber is nearly double that of upland cotton. We hypothesized that Pima cotton could be successfully cultivated in the southeast United States because of the eradication of the boll weevil, alongside improvements in genetics and production practices. We evaluated the agronomic performance, fiber quality, and net economic return of 48 Pima genotypes in field trials conducted during 2018 and 2019 in Florence, SC, compared with two popular commercial upland cultivars. We also evaluated the impact of the ginning method (saw vs. roller) on fiber quality. On average, in comparison with upland cotton, the lint yield of Pima genotypes was reduced by half. However, most of the Pima genotypes produced higher-quality fibers compared with the upland checks. Surprisingly, the ginning method appeared to have little impact on fiber quality. Net return analysis revealed no significant differences among several of the higher-yielding, higher-quality Pima genotypes and the upland genotypes in this study, indicating that the reintroduction of a Pima production system in the southeast United States may be feasible.

1 | INTRODUCTION

Cotton production in the United States involves the cultivation of two species of *Gossypium* spp., with upland cotton (*Gossypium hirsutum* L.) being the most widely cultivated. Pima cotton (*Gossypium barbadense* L.) (also known as Sea Island, Egyptian, or extra-long staple cotton) is produced in more arid regions of the western United States. On a global scale, Pima cotton only accounts for approximately 3 to 5% of the total cotton production, whereas upland cotton accounts for the majority of the remainder (Fang, 2018). William Elliot was the first person to cultivate *G. barbadense* in the United States at Hilton Head Island, SC, in 1790 (Mcgowan, 1960). In the early 20th century, Pima cotton was produced in the southeast United States near the coasts of South Carolina and Georgia, and in northern Florida. This continued into the early 1900s, with farmers producing both upland and Pima cotton until the boll weevil (*Anthonomus grandis grandis* Boh.) invaded the Cotton Belt. This caused southeastern growers to switch to producing only shorter-season upland cotton to escape yield and economic losses. Later, in the 1930s, there were efforts to improve upland cotton fiber quality by introgressing fiber traits from Pima into upland cultivars, but those cultivars were only in commercial production until the 1950s

(Kumar et al., 2019). Today, upland cotton remains the only species of cotton produced commercially in the southeast United States, accounting for approximately $1.7 billion USD in 2019, with 1.2 million ha planted across Alabama, Georgia, Florida, South Carolina, North Carolina, and Virginia (USDA–National Agricultural Statistics Service, 2020).

Production of Pima cotton began in the western United States in the late 1940s. The first Pima variety, 'Pima S-1′, was developed in 1951 (Bryan, 1955), followed by the development of six other major Pima varieties in Arizona, New Mexico, and West Texas. These varieties were developed by the USDA-ARS, who released the Pima varieties 'S-2′, 'S-3′, 'S-4′, 'S-5′, 'S-6′, and 'S-7′ between 1960 and 1991 (Turcotte et al., 1992). California began producing Pima cotton in the late 1980s, as only one strain of upland cotton could be grown in the San Joaquin Valley from 1925 to 1978 in order to prevent the crossing of superior strains with inferior ones (Geisseler & Horwath, 2013). Between these four states, ∼92,552 ha of Pima cotton were planted in 2019 (USDA–National Agricultural Statistics Service, 2019).

For specialized textile applications requiring higher count yarns and premium fabrics, Pima cotton is preferred over upland because it is known to produce longer, stronger, finer, and more uniform fibers. On average, upland genotypes range in fiber length from 22.4 to 33.3 mm, whereas Pima fiber lengths range from 31.8 to 50.8 mm (Cotton Incorporated, 2018). The minimum fiber length for Pima cotton must exceed 34.9 mm to receive a premium (USDA–Farm Service Agency, 2019). Upland genotypes range in fiber strength, with lower classes falling below 226 kN m kg^{-1} and higher classes above 304 kN m kg^{-1} (Islam et al., 2016). Pima cotton has stronger fibers than upland cotton and requires a minimum strength reading of 363 kN m kg^{-1} to avoid discounted fiber quality (USDA–Farm Service Agency, 2019). The premium micronaire range, which is a measure of fiber fineness and maturity, is between 3.7 and 4.2 for upland cotton; premiums for micronaire in Pima cotton do not currently exist. However, micronaire values for Pima cotton need to exceed a minimum of 3.5 in order to avoid discounted fiber quality (USDA–Farm Service Agency, 2019). Because of its superior fiber quality and processing ability, Pima cotton fiber is typically valued two times higher than upland cotton fiber (USDA–Agricultural Marketing Service, 2020). Successful cultivation of Pima cotton could boost the economic impact of cotton production in the southeast.

Although upland cotton is most often ginned on a commercial saw gin, Pima cotton is typically ginned on a roller gin. Roller ginning is usually more expensive than saw ginning; however, with Pima being considerably more valuable than upland cotton, it is important to preserve its premium fiber quality by using the gentlest ginning method possible. Several studies indicate that roller ginning produces higher quality fibers than saw ginning (Armijo & Gillum, 2010). Wanjera et al. (2012) found that fiber lengths were significantly improved for an upland genotype when ginned on a high-speed roller gin as opposed to a conventional saw gin. The reciprocating knife roller gin, invented by Fones McCarthy, was the first major roller gin to be used, beginning in the 1840s, and was used almost exclusively on Pima cotton (Thomas et al., 2008). This type of roller gin uses a 20-cm ginning roller that captures the lint and pulls the seed to a stationary knife that removes the lint from the seed more gently than the saw gin. The reciprocating knife then dislodges and releases the seeds. Roller gins of this type were only able to produce ∼91 kg of lint per hour, whereas more modern roller gins used today, referred to as high-capacity roller gins, can produce close to 318 kg of lint per hour by using a larger 38-cm ginning roller (Thomas et al., 2008). The high-capacity roller gin used for ginning Pima cotton in the United States is referred to as a rotary-knife roller gin and was invented by the USDA-ARS Southwestern Cotton Ginning Research Laboratory in Mesilla Park, NM, in the late 1950s and is commercially available from Lummus Corp. today (Armijo et al., 2017).

Core Ideas

- Compared with upland genotypes, Pima genotypes had premium fiber quality but yielded 50% less.
- The ginning method had little impact on fiber quality parameters.
- The net return of the highest-yielding Pima genotypes was not different from the upland checks.

After nearly a century of only upland cotton being produced in the southeast United States, research on the adaptation, agronomic performance, and feasibility of producing Pima cotton is needed to determine if it can be produced commercially in the region today. Today, most of the barriers that led to the shift away from Pima to Upland cotton production in the southeast United States no longer exist, especially since the boll weevil has now been successfully eradicated from all cotton-producing states east of Texas. The main goals of this study were to identify Pima genotypes that have acceptable yield and fiber quality when grown in South Carolina, and to determine if roller ginning would be necessary to preserve its premium fiber quality.

2 | MATERIALS AND METHODS

A 2-yr field study was conducted at the Clemson University Pee Dee Research and Education Center in Florence, SC,

TABLE 1 Tests of fixed effects for lint yield, gin turnout, fiber quality, and net return for 50 cotton genotypes evaluated in Florence, SC, in 2018 and 2019 when ginned on a 10-saw gin and sampled from grab samples obtained from the cotton picker

Source of variation	df[a]	Lint yield	Gin turnout	Fiber length	Fiber strength	Micronaire	Uniformity	Net return
		F-ratio						
Year	1	184.8**	0.1	53.6**	433.8**	1364.6**	152.6**	196.5**
Genotype	49	42.7**	29.5**	14.7**	31.0**	16.9**	6.2**	15.7**
Genotype × year	49	3.0**	1.0	0.88	2.0**	1.2	1.9**	2.8**

[a] Error df = 294.

*Significant at the .05 level of probability. **Significant at the and 0.01 level of probability.

in 2018 and 2019 on a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic Aquic Paleudults). The study was planted on 3 May 2018 and 1 May 2019 with a JD 7200 planter (John Deere) equipped with individual cone-planter units at a seeding rate of 13 seed m^{-2}. Fifty genotypes were evaluated, which consisted of two high-yielding, high-fiber quality commercial Upland checks ('Deltapine 1646B2XF' and 'Phytogen 444WRF'), five commercial Pima genotypes ('Phytogen 881RF', 'Phytogen 841RF', 'Phytogen 805RF', 'Deltapine 358RF', and 'Deltapine 348RF'), and 43 Pima accessions that contained Egyptian genotypes ('Giza 80', 'Giza 67', 'Giza 45', 'Giza 4', 'Menoufi', 'Afifi', 'Ashabad 8', 'Ashabad 11', 'Ashabad 1615', 'Karnak', 'Karnak 55', and 'Ashmouni 235'), American Pima genotypes ('Pima S2', 'Pima S3', 'Pima S4', and 'Pima S6'), elite breeding strains ('P 62', 'P 65', 'P 76', and 'P 79'), and two Sea Island genotypes ('Seabrook Sea Island' and 'Puerto Rican Sea Island'). All Pima genotypes used in this trial were previously evaluated in a nonreplicated observation plot grown at the Pee Dee Research and Education Center in 2016 extracted from a set of 155 Pima accessions obtained from the USDA-ARS Cotton Germplasm Collection in College Station, TX. Of all 155 accessions, 43 were selected on the basis of their growth habit and number of bolls produced. In 2017, seed was increased in Maricopa, AZ to be used for this study.

The genotypes were planted in a randomized complete block design that contained four replications. Genotypes were planted in two-row plots that were 0.97 m wide and 12.2 m long. 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*. Moreover, at planting, a tank-mixture of 0.43 kg ha^{-1} of formesafen and 1.10 kg ha^{-1} of pendimethalin was soil applied before emergence to all plots. Postemergence weed control was accomplished through post-directed applications of 2.30 kg ha^{-1} of monosodium acid methanearsenate and 0.85 kg ha^{-1} of prometryn. All herbicide applications were applied uniformly at the appropriate time of crop development and hand-weeding was used when necessary to keep the plots weed-free. An ammonium sulfate solution was applied at 90 kg N ha^{-1} at the pinhead to matchhead square stage of development. Plots were irrigated twice during the 2018 growing season with 2.54 cm applied on 9 July 2018 and 2.54 cm on 16 July 2018. Plots were irrigated three times throughout the 2019 growing season with 2.0 cm on 29 May 2019 and 2.54 cm on 2 July and 8 Aug. 2019.

All 200 plots were harvested on 24 Oct. 2018 (172 d after planting) and 30 Sept. 2019 (152 d after planting) with a Case IH 1822 two-row spindle-picker modified with an on-board weighing system for small research plots. Each two-row plot was harvested and weighed, and samples of ∼250 to 350 g of seed cotton (grab samples) were obtained for ginning and evaluation of fiber quality. In 2019, in addition to the grab samples obtained from the cotton picker, a 50-boll sample was hand-harvested from first-position bolls in the middle of the plant to provide samples with less trash or debris. Each sample (grab and hand-harvested) was split into two equal portions. One portion was ginned on a laboratory 10-saw gin (Continental Gin Co.) and the second portion on a laboratory roller gin that included a lint cleaner (Olvey and Associates). In both 2018 and 2019, saw gin data from the grab samples were used to calculate the lint percentage or gin turnout (in percent) and lint yield on a kg ha^{-1} basis. All samples for roller ginning were obtained from grab samples in 2018 and hand-harvested samples in 2019. Gin turnout data were obtained from the roller ginning process only in 2019. Hand-harvested samples were only used to make the comparisons between ginning methods regarding gin turnout in 2019. Following ginning, ∼30 g of lint was obtained from each ginning process and sent to the Texas Tech University Fiber and Biopolymer Research Institute in Lubbock, TX, to be evaluated on a high-volume instrument (HVI) calibrated for Pima cotton each year. Fiber properties obtained from the high-volume instrument included fiber length, fiber strength, micronaire, and uniformity. Net return values were obtained from Cotton Incorporated's Loan Calculator (Cotton Incorporated, 2019), which combined the value of the lint (with the premiums and discounts for fiber quality included) and the

TABLE 2 Lint yield, gin turnout, fiber quality, and net returns for 50 cotton genotypes grown at the Pee Dee Research and Education Center in Florence, SC, in 2018 when grab samples were ginned on a 10-saw gin. Genotypes are in order from highest to lowest net return in 2018

Genotype	PI No.	Lint yield	Gin turnout	Fiber length	Fiber strength	Micronaire	Uniformity	Net Return
		kg ha^{-1}	%	mm	kN m kg^{-1}		%	\$ ha^{-1}
P 76	PI 593684	667	40.5	32.7	268	3.6	84.0	1,290
Deltapine 1646B2XF	–	1,281	45.9	30.7	267	4.0	82.2	1,273
P 65	PI 604383	628	39.3	34.3	317	3.7	83.3	1,198
P 79	PI 593687	586	38.2	34.0	345	3.7	83.7	1,114
E 14	PI 604456	583	37.7	32.9	376	3.6	83.5	1,112
Phytogen 841RF	–	575	43.6	33.1	353	3.4	84.1	1,082
'STD 5'	–	561	39.0	32.6	348	3.5	83.5	1,048
Deltapine 348RF	–	538	41.0	32.8	325	3.5	84.5	1,006
Giza 80	PI 630111	528	36.4	33.3	349	3.7	83.8	998
Phytogen 805RF	–	526	43.5	32.1	366	3.5	83.5	991
Phytogen 881RF	–	504	42.9	33.2	333	3.5	83.7	959
Pima S6 (528)	–	504	42.6	32.8	342	3.5	83.1	951
'STD 4'	–	494	36.7	32.8	332	3.6	82.4	927
P 62	PI 542773	481	38.1	32.1	326	3.7	83.8	914
Phytogen 444WRF	–	955	44.1	30.9	351	3.4	82.3	899
Deltapine 358RF	–	495	39.9	32.9	376	3.1	84.3	895
Pima S3 (K6564)	PI 630114	469	37.7	31.3	386	3.6	82.2	882
'Tadla 116' (492)	PI 608194	456	34.4	33.5	342	3.5	83.4	867
'8327'	PI 561923	455	38.0	33.3	341	3.4	84.2	850
Giza 67	PI 630108	445	36.4	34.0	330	3.6	83.2	835
Tadla 116 (K7427)	–	429	36.7	31.9	355	4.0	82.5	823
Pima S6 (498)	PI 608346	435	36.5	32.1	354	3.5	82.6	818
'85414'	PI 561924	407	40.7	30.4	386	3.9	81.8	786
'89590'	PI 599427	433	39.4	33.2	386	3.2	83.4	783
Assili	PI 528367	447	37.1	35.6	341	2.9	83.1	771
'Faudu 928'	PI 630078	408	34.0	33.1	401	3.5	82.8	764
GIZA 4	–	426	34.1	32.7	335	3.1	82.2	754
Puerto Rican Sea Island	PI 152420	416	35.4	32.1	327	3.3	83.1	749
'85424'	PI 561925	387	38.5	31.4	325	4.0	81.9	741
'7318-V'	PI 608177	390	37.6	33.0	340	3.5	83.2	736
Karnak	PI 407504	402	35.2	33.5	374	3.4	83.4	731
Ashabad 1615	PI 608182	369	34.0	33.0	339	3.9	83.6	699
Seabrook Sea Island	PI 608348	370	36.0	34.9	325	3.6	84.1	699
Pima S4	PI 529533	405	34.3	33.6	337	2.9	83.3	697
'Baracat'	–	362	36.8	33.2	329	3.5	83.6	677
'CNH-67'	–	350	36.3	32.8	328	3.7	82.8	667
'9075'	PI 630070	351	33.5	33.2	338	3.4	83.8	642
Ashabad 8	PI 608172	346	32.7	33.9	337	3.4	83.4	628
Menoufi	PI 407506	331	34.6	32.6	325	3.5	82.6	620
'Palmyra 27'	PI 407507	327	36.0	30.4	357	3.5	81.2	618
Giza 45	PI 407501	334	33.7	34.0	337	3.4	84.9	615
Ashabad 11	PI 608197	344	36.5	33.9	324	3.0	84.5	605
Pima S3	PI 608211	318	35.3	34.4	317	3.4	82.6	586

(Continues)

TABLE 2 (Continued)

Genotype	PI No.	Lint yield	Gin turnout	Fiber length	Fiber strength	Micronaire	Uniformity	Net Return
‘Piliona 35’	PI 636073	300	37.3	30.1	322	4.0	80.1	573
Afifi	PI 630075	294	34.8	33.1	307	3.4	83.8	541
Ashmouni 235	PI 630077	274	33.2	32.7	329	3.7	83.9	519
‘Raleigh Stock’	PI 608120	280	34.4	34.3	335	3.4	84.0	511
Pima S2 (K4781)	–	276	35.8	34.4	330	3.2	84.6	494
Karnak 55	PI 407505	270	34.8	32.2	316	3.3	81.5	489
Bleak Hall	PI 608115	152	33.3	37.8	307	2.7	82.1	245
Standard error		47.6	1.09	0.62	7.96	0.11	0.58	85.7
Trial mean		447	37.3	33.0	339	3.5	83.2	793
LSD (.05)		125	3.0	1.8	22	0.3	1.6	222

value of the seed, and subtracted the cost of ginning (saw) and harvesting.

All data were analyzed via a mixed model in JMP Pro 14.3 software (SAS Institute Inc.) with the random effect of block nested within year and the fixed effects of year, genotype, and genotype × year. If significant genotype × year interactions were detected, the data were analyzed separately between the years and reported individually. If no significant genotype × year interactions were detected, the data were combined across years. Comparisons among means were made for lint yield, gin turnout, fiber length, fiber strength, micronaire, and uniformity via Fisher’s protected LSD test at the .05 level of probability.

In addition, the differences between the saw gin and roller gin were calculated for fiber length, strength, and micronaire on a per-plot basis. Differences in gin turnout between the roller and saw gin were investigated in the hand-harvested samples on a per-plot basis in 2019 only. Mean differences among genotypes for each fiber quality parameter were tested via the mixed model previously described. If significant genotype × year interactions were detected, the data were analyzed separately between the years and reported individually. If no significant genotype × year interactions were detected, the data were combined across years. If the lower and upper confidence intervals for each mean difference for each fiber quality parameter did not include a value of zero, the two ginning methods were considered to be different. If the mean difference was positive for a genotype and the confidence interval excluded zero, the saw gin had a significantly higher value. If the mean difference was negative for a genotype and the confidence interval excluded zero, the roller gin had a significantly higher value. For the net return analysis, Pima genotypes were compared with the upland checks for both years of the study by using the Pima base loan rate of \$2.09 kg^{-1} and the upland base loan rate of \$1.15 kg^{-1}, and by using the upland criteria for premiums and discounts for both the upland and Pima genotypes.

3 | RESULTS AND DISCUSSION

There was a significant genotype × year interaction for both yield and fiber quality parameters (excluding saw-ginned fiber length and micronaire data collected from grab samples); therefore, yield and fiber quality data are reported as separate years (Table 1). There were significant differences among genotypes for both yield and fiber quality parameters (Table 2, Table 3). Lint yields were higher in 2019 than in 2018, with a 37% increase between the years (Table 1, Table 2, Table 3). Growing conditions varied greatly between the years of the study. In 2018, heavy wind and rainfall occurred just prior to harvest from two tropical cyclones. Harsh weather conditions in 2019 probably resulted in lower yields and fiber quality because of the detrimental effects on lower fruiting positions on the crop. In 2019, average rainfall and temperatures occurred during the growing season.

In 2018, the trial mean for lint yield was 447 ± 47.6 kg ha^{-1} versus 714 ± 44.1 kg ha^{-1} in 2019. In general, the upland checks produced ~60% higher yield than the Pima genotypes in both years of the study. In 2018, the upland checks averaged 1,118 kg ha^{-1} and the Pima genotypes averaged 419 kg ha^{-1}. In 2019, the upland checks averaged 1,682 kg ha^{-1}, whereas the Pima genotypes averaged 689 kg ha^{-1}. More specifically, the commercial Pima genotypes had an average lint yield of 528 kg ha^{-1} (2018) and 790 kg ha^{-1} (2019), the Egyptian genotypes averaged 364 kg ha^{-1} (2018) and 656 kg ha^{-1} (2019), the American Pima genotypes averaged 401 kg ha^{-1} (2018) and 614 kg ha^{-1} (2019), the Sea Islands genotypes averaged 393 kg ha^{-1} (2018) and 766 kg ha^{-1} (2019), the elite breeding strains averaged 590 kg ha^{-1} (2018) and 780 kg ha^{-1} (2019), and the remaining Pima genotypes averaged 399 kg ha^{-1} (2018) and 639 kg ha^{-1} (2019). In 2018, the elite breeding strains had a significantly higher ($p = .0219$) average lint yield than the commercial Pima genotypes; the other five groups of Pima genotypes all had significantly lower ($p < .0001$) lint yields than the commercial Pima

TABLE 3 Lint yield, gin turnout, fiber quality, and net return for 50 cotton genotypes grown at the Pee Dee Research and Education Center in Florence, SC, in 2019 when grab samples were ginned on a 10-saw gin. Genotypes are in order from highest to lowest net return in 2019

Genotype	PI No.	Lint yield	Gin turnout	Fiber length	Fiber strength	Micronaire	Uniformity	Net return
		kg ha^{-1}	%	mm	kN m kg^{-1}		%	$ ha^{-1}
Deltapine 1646B2XF	–	1,856	47.0	30.9	294	4.7	84.3	1,856
P 79	PI 593687	865	39.2	33.8	412	4.2	84.5	1,665
Phytogen 805RF	–	850	42.4	33.7	449	3.9	86.4	1,653
Phytogen 881RF	–	841	42.8	35.0	446	4.1	88.2	1,636
8327	PI 561923	846	39.0	34.2	396	4.0	85.1	1,631
E 14	PI 604456	838	38.5	33.6	401	4.0	85.7	1,614
Giza 4	–	856	34.3	33.3	359	3.5	84.7	1,581
89590	PI 599427	811	40.4	33.0	405	4.2	85.7	1,569
Phytogen 841RF	–	800	42.5	34.0	459	4.1	86.9	1,557
85414	PI 561924	805	39.5	32.6	415	4.4	84.9	1,552
Phytogen 444WRF	–	1,510	45.2	31.2	313	4.1	85.8	1,515
P 62	PI 542773	786	38.5	31.6	373	4.2	82.4	1,512
Seabrook Sea Island	PI 608348	786	36.1	34.7	418	4.0	85.2	1,502
Assili	PI 528367	794	38.3	35.8	457	3.7	87.2	1,497
Karnak	PI 407504	771	34.8	34.9	393	3.8	86.0	1,470
Deltapine 348RF	–	748	40.6	33.5	459	3.9	86.5	1,448
P 65	PI 604383	746	40.0	35.9	417	4.1	86.5	1,443
Puerto Rican Sea Island	PI 152420	746	36.3	34.1	375	3.9	85.3	1,428
Tadla 116 (K7427)	–	731	37.4	32.6	376	4.5	83.1	1,401
P 76	PI 593684	724	38.7	33.3	436	3.9	85.8	1,396
Faudi 928	PI 630078	731	33.6	34.4	371	3.9	85.8	1,389
Giza 67	PI 630108	710	37.6	35.1	394	4.1	85.9	1,364
Pima S6 (528)	–	705	39.7	33.7	379	4.0	85.7	1,362
Deltapine 358RF	–	712	39.8	34.1	442	3.7	86.3	1,357
Ashabad 11	PI 608197	701	36.1	34.9	391	3.5	86.4	1,342
Tadla 116 (492)	PI 608194	682	35.0	34.0	372	4.1	85.4	1,300
Pima S4	PI 529533	679	35.6	34.0	386	3.5	85.4	1,270
Ashmouni 235	PI 630077	664	33.0	32.8	380	4.2	85.3	1,255
Giza 80	PI 630111	657	35.7	33.8	381	4.3	85.1	1,255
Pima S6 (498)	PI 608346	651	37.0	33.0	368	4.0	83.9	1,243
Menoufi	PI 407506	645	35.3	34.4	367	4.2	85.9	1,231
STD 5	–	636	39.6	33.0	387	4.0	84.2	1,226
Afifi	PI 630075	641	35.6	33.5	365	4.0	85.3	1,226
STD 4	–	626	39.3	34.2	389	3.9	85.8	1,208
7318-V	PI 608177	622	35.3	33.7	376	3.9	85.0	1,189
CNH-67	–	603	37.6	34.1	369	4.3	84.7	1,156
Baracat	–	599	36.9	34.5	368	3.8	85.8	1,149
Ashabad 8	PI 608172	597	34.6	35.2	373	3.9	86.4	1,137
Ashabad 1615	PI 608182	599	32.9	33.4	384	4.6	85.0	1,134
Pima S3 (K6564)	PI 630114	584	38.2	30.6	342	4.4	82.9	1,122
85424	PI 561925	563	38.9	32.2	389	4.4	82.9	1,082
Piliona 35	PI 636073	562	35.4	31.6	382	4.5	83.3	1,070
Pima S3	PI 608211	553	35.5	35.9	372	3.8	85.7	1,055

(Continues)

TABLE 3 (Continued)

Genotype	PI No.	Lint yield	Gin turnout	Fiber length	Fiber strength	Micronaire	Uniformity	Net return
9075	PI 630070	555	33.9	34.4	380	3.9	86.1	1,055
Palmyra 27	PI 407507	542	35.8	32.7	363	3.9	84.5	1,035
Giza 45	PI 407501	545	33.5	34.6	371	4.0	85.9	1,035
Pima S2 (K4781)	–	512	36.4	35.4	389	3.7	87.3	981
Raleigh Stock	PI 608120	508	34.1	35.8	374	3.7	86.5	969
Karnak 55	PI 407505	487	34.8	34.1	369	3.6	84.1	929
Bleak Hall	PI 608115	82	29.8	39.3	352	3.3	83.3	146
Standard error		44.1	0.42	0.38	6.97	0.08	0.51	82.9
Trial mean		714	37.3	33.9	388	4.0	85.3	1304
LSD (.05)		123	1.2	1.1	20	0.2	1.4	232

TABLE 4 Genotypes displaying a significant response ($p < .05$) to ginning method for fiber length and strength. Fiber length and strength data were combined over years as there were no significant genotype × year interactions for the differences between the 10-saw gin and roller gin data

Genotype	PI No.	Fiber length Roller gin	Saw gin
		mm	
8327	PI 561923	35.1*	33.8
Palmyra 27	PI 407507	32.8*	31.5
Giza 80	PI 630111	35.1*	33.5
Pima S3	PI 608211	36.8*	35.1
Piliona 35	PI 636073	32.5*	30.7
Bleak Hall	PI 608115	42.7*	38.6
ASSILI	PI 528367	34.8	35.8*
		Fiber strength	
		Roller gin	**Saw gin**
		kN m kg^{-1}	
P 79	PI 593687	302	394*
P 62	PI 542773	330	353*
85424	PI 561925	340	362*
Tadla 116 (K7427)	–	342	359*

*Significantly different from the other ginning method at the .05 level of probability.

TABLE 5 Tests of fixed effects for the differences between two ginning methods for micronaire for 50 cotton genotypes evaluated in Florence, SC, in 2018 and 2019

Parameter	df	Mean squares	*F*-ratio
Year	1	0.66	9.28*
Genotype	49	0.21	3.62**
Genotype × year	49	0.11	1.88**

*Significantly different at the .05 level of probability. **Significantly different at the.01 levels of probability.

genotypes. In 2019, the average lint yields of the elite Pima breeding strains and the Sea Island Pima genotypes did not differ significantly ($p = .7837$ and $p = .5016$, respectively) from the commercial Pima genotypes, whereas the other four groups of Pima genotypes had significantly lower ($p < .0001$) lint yields than the commercial Pima genotypes. In both years, P 79 and 'E 14' were among the top six highest-yielding Pima genotypes, with P 79 having an average lint yield of 586 kg ha^{-1} (2018) and 865 kg ha^{-1} (2019) and E 14 averaging 583 kg ha^{-1} (2018) and 838 kg ha^{-1} (2019) (Table 1, Table 2). The Pima genotype 'Bleak Hall', was the lowest-yielding genotype in both years of the study, averaging 152 kg ha^{-1} (2018) and 82 kg ha^{-1} (2019).

The lint yield of some genotypes differed significantly between the years, explaining the significant genotype × year interaction shown in Table 1. The Egyptian cultivar Giza 4 fell below the top 20 highest-yielding Pima genotypes in 2018, with an average lint yield of 426 kg ha^{-1}, but was among the top six highest-yielding Pima genotypes in 2019, with an average lint yield of 856 kg ha^{-1}. In 2018, P 76 and P 65 were the top two highest-yielding Pima genotypes, with P 76 yielding 667 kg ha^{-1} and P 65 yielding 628 kg ha^{-1}; however, in 2019, P 76 was only the 18th highest-yielding Pima genotype, with an average lint yield of 724 kg ha^{-1}, and P 65 was the 15th highest-yielding Pima genotype, with an average lint yield of 746 kg ha^{-1} (Table 2, Table 3). The shift in ranking for lint yield was common for several other Pima genotypes and highlights the influence of genotype × environment interactions, probably as a consequence of poor adaptation to southeastern United States growing environments.

The average gin turnout did not increase significantly from 2018 to 2019 on the saw gin, with a trial mean of 37.3% ± 1.09 in 2018 and 37.3% ± 0.42 in 2019; however, there were significant differences among genotypes each year (Table 1, Table 2, Table 3). In 2018, the upland checks had an average gin turnout of 45.0% compared with the Pima genotypes (37.0%). In 2019, the upland checks had an average

TABLE 6 Micronaire of genotypes displaying a significant response ($p < .05$) to ginning method in 2018 and 2019

		Micronaire			
		2018		2019	
Genotype	PI No.	Roller gin	Saw gin	Roller gin	Saw gin
Deltapine 1646B2XF	–	4.3*	4.0	5.1*	4.7
Ashabad 1615	PI 608182	4.0	3.9	4.9*	4.6
Piliona 35	PI 636073	4.2	4.0	4.9*	4.5
Tadla 116 (K7427)	–	4.2	4.0	4.9*	4.5
85414	PI 561924	4.4*	3.9	4.9*	4.4
Pima S3 (K6564)	PI 630114	4.0*	3.6	4.6	4.4
85424	PI 561925	4.1	4.0	4.7*	4.4
GIZA 80	PI 630111	4.1*	3.7	4.6*	4.3
CNH-67	–	3.9	3.7	4.5	4.3
P 62	PI 542773	3.9	3.7	5.0*	4.2
Ashmouni 235	PI 630077	3.9	3.7	4.7*	4.2
Menoufi	PI 407506	3.7	3.5	4.4	4.2
89590	PI 599427	3.3	3.2	4.6*	4.2
P 79	PI 593687	4.0*	3.7	4.7*	4.2
Tadla 116 (492)	PI 608194	3.9*	3.5	4.7*	4.1
Phytogen 841RF	–	3.8*	3.4	4.7*	4.1
Giza 67	PI 630108	3.8*	3.5	4.4*	4.1
Phytogen 881RF	–	3.9*	3.5	4.5*	4.1
Phytogen 444WRF	–	3.7*	3.4	4.8*	4.1
P 65	PI 604383	4.1*	3.7	4.4*	4.1
Afifi	PI 630075	4.0*	3.4	4.5*	4.0
E 14	PI 604456	4.0*	3.6	4.5*	4.0
STD 5	–	3.7	3.5	4.4*	4.0
Pima S6 (498)	PI 608346	3.8*	3.5	4.5*	4.0
Seabrook Sea Island	PI 608348	4.0*	3.6	4.4*	4.0
Giza 45	PI 407501	3.7*	3.4	4.1	4.0
8327	PI 561923	3.7*	3.4	4.5*	4.0
Pima S6 (528)	–	3.8*	3.5	4.2	4.0
Faudu 928	PI 630078	3.9*	3.5	4.4*	3.9
Puerto Rican Sea Island	PI 152420	3.5	3.3	4.2*	3.9
Palmyra 27	PI 407507	3.8	3.6	4.4*	3.9
P 76	PI 593684	3.9*	3.6	4.3*	3.9
7318-V	PI 608177	3.6	3.5	4.4*	3.9
STD 4	–	3.8*	3.6	4.4*	3.9
Deltapine 348RF	–	4.0*	3.5	4.1	3.9
9075	PI 630070	3.7*	3.4	4.1	3.9
Phytogen 805RF	–	3.8*	3.5	4.2*	3.9
Ashabad 8	PI 608172	3.6*	3.4	4.1	3.9
Baracat	–	3.7	3.5	4.4*	3.8
Karnak	PI 407504	3.5	3.4	4.2*	3.8
Pima S3	PI 608211	3.6	3.4	4.5*	3.8
Raleigh Stock	PI 608120	3.4	3.4	4.0*	3.7
Deltapine 358RF	–	3.6*	3.1	3.9	3.7
Pima S2 (K4781)	–	3.6*	3.2	3.9	3.7
Assili	PI 528367	3.7*	2.9	4.2*	3.7
Karnak 55	PI 407505	3.4	3.3	3.9*	3.6
Ashabad 11	PI 608197	3.4*	3.0	3.8*	3.5
Pima S4	PI 529533	3.2*	2.9	3.9*	3.5
Giza 4	–	3.4*	3.1	4.0*	3.5
Bleak Hall	PI 608115	2.5	2.7	2.4	3.3*
Standard error		0.12	0.105	0.097	0.08
Trial mean		3.8	3.5	4.4	4.0
LSD (.05)		0.34	0.30	0.27	0.23

*Significantly different from the other ginning method at the .05 level of probability.

gin turnout of 46.1%, whereas the Pima genotypes averaged 37.0% (Table 1, Table 2, Table 3). The commercial Pima genotypes had the highest gin turnout ($p < .0001$) of all the Pima genotypes, with an average gin turnout of 42.2% (2018) and 41.6% (2019). The Egyptian genotypes had an average gin turnout of 34.7% (2018) and 34.8% (2019), the American Pima cultivars averaged 37.0% (2018) and 37.1% (2019), the Sea Islands genotypes averaged 35.7% (2018) and 36.2% (2019), the elite breeding strains averaged 39.0% (2018) and 39.1% (2019), and the remaining Pima genotypes averaged 36.7% in both 2018 and 2019.

The net return values for the top five highest-yielding Pima genotypes (for the Pima base loan rate of \$2.09 kg^{-1}) and the two upland checks (for the upland base loan rate of \$1.15 kg^{-1}) were all compared and no significant differences between the values were observed for either year of the study ($p = .3470$ in 2018 and $p = .1666$ in 2019). However, there were significant differences among the 50 genotypes each year (LSD (.05) = 222 in 2018 and 232 in 2019), where the Pima accession P 76 had the highest net return of all the genotypes in 2018, with a net return of \$1,290 ha^{-1}, and P 79 had the highest net return of all the Pima genotypes in 2019, with a net return of \$1,665 ha^{-1}. The upland checks averaged a net return of \$1,056 ha^{-1} in 2018 and \$1,686 ha^{-1} in 2019, with Deltapine 1646B2XF having the higher net return of the two each year because of its superior yield. The range of net return values for the Pima genotypes ranged from \$245 to \$1,290 ha^{-1} in 2018 and from \$146 to \$1,665 ha^{-1} in 2019,

TABLE 7 Comparisons of gin turnout between two ginning methods for hand-harvested boll samples from 50 cotton genotypes grown at the Pee Dee Research and Education Center in Florence, SC, in 2019

Genotype	PI No.	Gin turnout	
		Saw gin	Roller gin
		%	
Deltapine 1646B2XF	–	48.7	49.9
Phytogen 444WRF	–	48.2	48.7
Phytogen 881RF	–	42.3	44.8*
Phytogen 841RF	–	41.8	44.9*
Phytogen 805RF	–	41.0	43.3*
Deltapine 348RF	–	41.0	42.1
89590	PI 599427	40.5	42.6*
P 62	PI 542773	40.4	39.7
Deltapine 358RF	–	40.2	41.6
Pima S6 (528)	–	39.4	40.2
85414	PI 561924	39.0	41.1*
P 79	PI 593687	38.8	41.7*
STD 4	–	38.7	40.2
STD 5	–	38.5	39.6
E 14	PI 604456	38.5	40.7*
P 76	PI 593684	38.2	40.7*
P 65	PI 604383	38.0	40.5*
8327	PI 561923	37.9	40.6*
85424	PI 561925	37.5	39.5*
Pima S6 (498)	PI 608346	37.1	39.2*
Assili	PI 528367	36.9	40.6*
Pima S3 (K6564)	–	36.7	37.3
Giza 67	PI 630108	36.4	38.4*
CNH-67	–	35.9	36.8
Tadla 116 (K7427)	–	35.5	37.8*
Baracat	–	35.4	37.6*
Pima S4	PI 529533	35.4	36.5
Seabrook Sea Island	PI 608348	35.2	36.5
Pima S2 (K4781)	–	35.1	36.7*
Puerto Rican Sea Island	PI 152420	35.0	36.4
Afifi	PI 630075	35.0	36.8*
Piliona 35	PI 636073	35.0	36.1
Palmyra 27	PI 407507	35.0	36.1
Giza 80	PI 630111	34.7	36.6*
Ashabad 11	PI 608197	34.3	36.9*
Pima S3	PI 608211	33.6	36.1*
Karnak	PI 407504	33.6	35.2*
Menoufi	PI 407506	33.4	35.0*
7318-V	PI 608177	33.2	33.9
Tadla 116 (492)	PI 608194	33.0	35.9*
Raleigh Stock	PI 608120	32.6	34.4*
Giza 4	–	32.5	34.6*
Faudu 928	PI 630078	32.4	34.0*
Karnak 55	PI 407505	32.3	34.1*
Ashabad 8	PI 608172	31.8	34.5*
9075	PI 630070	31.4	32.4
Giza 45	PI 407501	31.3	32.9*
Ashmouni 235	PI 630077	30.9	33.2*
Ashabad 1615	PI 608182	30.8	32.3*
Bleak Hall	PI 608115	20.5	19.8
Standard error		0.61	0.54
Trial mean		36.2	37.9
LSD (.05)		1.6	1.4

(Continues)

TABLE 7 (Continued)

*Significantly different from the other ginning method at the .05 level of probability.

with 'Bleak Hall' having the lowest net return in both years (Table 2 and Table 3). Similar to the higher lint yields in 2019, higher net returns also existed in 2019, with the trial mean increasing from \$793 ha^{-1} (2018) to \$1,304 ha^{-1} (2019). Although no significant differences in the net return appeared for the top five Pima genotypes and the upland checks in either year of the study, it is important to note that the net return values for the Pima genotypes were calculated with the upland cotton criteria for premiums and discounts for fiber quality and the Pima base loan rate of \$2.09 kg^{-1}. This created the best-case scenario for marketing Pima cotton in the southeast United States. Upland cotton criteria were used because the fiber lengths of most Pima genotypes in the study were lower than the minimum requirement for Pima cotton in the United States. If the Pima cotton criteria for premiums and discounts for fiber quality were used, the net returns may have been lower and significant differences may have been recognized.

Fiber length was significantly higher in 2019, with a trial mean of 33.0 ± 0.62 mm in 2018 and 33.9 ± 0.38 mm in 2019 for saw-ginned grab samples (Table 1, Table 2, Table 3) and 33.3 mm in 2018 and 34.5 mm in 2019 for roller-ginned samples (data not shown). In 2018, 35 Pima genotypes had significantly longer fibers than the upland checks when the grab samples were ginned on the saw gin. In 2019, 44 Pima genotypes had significantly longer fibers than the upland checks when the grab samples were ginned on the saw gin. The lowest-yielding Pima genotype, Bleak Hall, had significantly longer fibers than all other genotypes in both years of the study with either ginning method. Bleak Hall had an average fiber length of 37.8 mm in 2018 and an average fiber length of 39.3 mm in 2019 when the grab samples were ginned on the saw gin. Both values exceeded the minimum requirement for fiber length (34.9 mm) to receive the premium for Pima cotton in the United States. However, many Pima genotypes did not meet the minimum requirement, despite having significantly longer fibers than the upland checks. Only three Pima genotypes exceeded the minimum requirement for fiber length in 2018, and 10 exceeded the minimum requirement in 2019, which may suggest a lack of adaptation to the southeast United States on top of the crops being affected by two tropical cyclones in 2018.

Fiber strength increased significantly in 2019, with a trial mean of 339 ± 7.96 kN m kg^{-1} in 2018 and 388 ± 6.97 kN m kg^{-1} in 2019 for saw-ginned grab samples (Table 2 and Table 3). All 48 Pima genotypes had stronger fibers than the upland checks in both years of the study with either ginning method. The upland checks had an average fiber strength of 268 kN m kg^{-1} (2018) and 304 kN m kg^{-1} (2019), whereas the Pima genotypes averaged 342 kN m kg^{-1} (2018) and 391 kN m kg^{-1} (2019). In both 2018 and 2019, the five commercial Pima genotypes were among the top eight Pima genotypes with the strongest fibers. The commercial Pima genotypes had an average fiber strength of 385 kN m kg^{-1} In 2018 and an average strength of 451 kN m kg^{-1} in 2019. The top eight Pima genotypes with the strongest fibers in both years included Assili (366 kN m kg^{-1} in 2018 and 457 kN m kg^{-1} in 2019) and P 76 (389 kN m kg^{-1} in 2018 and 436 kN m kg^{-1} in 2019). The minimum strength requirement to avoid discounted fiber quality is 363 kN m kg^{-1} for Pima cotton in the United States. In 2018, only eight Pima genotypes exceeded the minimum requirement for fiber strength, despite each having significantly stronger fibers than the upland checks. However, in 2019, 40 of the 48 Pima genotypes exceeded the minimum requirement for fiber strength for Pima cotton in the United States, suggesting that the two tropical cyclones in 2018 may have negatively impacted fiber strength that year.

Micronaire increased significantly between years, with a trial mean of 3.5 ± 0.1 in 2018 and 4.0 ± 0.1 in 2019 for saw-ginned grab samples (Table 1, Table 2, Table 3). The upland checks averaged micronaire values of 3.7 (2018) and 4.4 (2019), whereas the Pima genotypes averaged 3.5 (2018 and 4.0 (2019). The minimum micronaire requirement for for Pima cotton in the United States is 3.5 in order to avoid discounted fiber quality. In 2018, 29 of the 48 Pima genotypes exceeded the minimum requirement for micronaire (3.5); in 2019, all the Pima genotypes (with the exception of Bleak Hall) met the minimum micronaire requirement (Table 2, Table 3). In both years, Bleak Hall had the lowest micronaire value (2.7 in 2018 and 3.3 in 2019) of all the genotypes tested. In addition to micronaire, fiber uniformity increased significantly between years, with a trial mean of 83.2% ± 0.58 in 2018 and 85.3% ± 0.51 in 2019 for saw-ginned grab samples (Table 1, Table 2, Table 3). The upland checks averaged 82.3% for 2018 and 85.0% for 2019, whereas the Pima genotypes averaged slightly higher at 83.2% for 2018 and 85.3% for 2019. In 2018, 38 Pima genotypes had numerically higher uniformity then the average of the upland checks; in 2019, 33 Pima genotypes had numerically higher uniformity than the average of the upland checks. The Egyptian Pima genotype Giza 45 had the most uniform fibers in 2018, with 84.9% uniformity (Table 2), and the commercial Pima genotype Phytogen 881RF had the most uniform fibers of 2019, with 88.2% uniformity (Table 3).

The differences in fiber length and strength between ginning methods did not have a significant genotype × year interaction; therefore, the data were combined across years. Only 7 of the 48 Pima genotypes displayed a significant response to ginning method for fiber length, with six of them performing significantly better on the roller gin and one (Assili) performing significantly better on the saw gin (Table 4). For fiber strength, only four showed a significant response to ginning method, with all four having significantly stronger fibers on the saw gin (Table 4). This may be because samples ginned on the roller gin were cleaned with a lint cleaner prior to ginning, which may have affected fiber strength. Several genotypes showed numerically longer or stronger fibers on one type of gin, but these differences were not statistically significant at the 95% probability level.

Micronaire values were higher on the roller gin as opposed to the saw gin, and there was a significant difference between years and a significant genotype × year interaction (Table 5). Micronaire values were increased significantly in fiber ginned on the roller gin in both years of the study with 31 genotypes producing significantly higher micronaire values on the roller gin in 2018 and 39 in 2019, with the exception of Bleak Hall, which had a significantly higher micronaire values on the saw gin in 2019 (Table 6). The trial mean for micronaire readings was 3.8 in 2018 and 4.4 in 2019 for roller-ginned samples (Table 6). The significant interactions with year and genotype × year could also be related to the different weather conditions experienced between the years, where higher-yielding environmental conditions in 2019 resulted in higher micronaire values, as micronaire and yield are often positively correlated (Campbell et al., 2012).

The trial mean for gin turnout was not significantly lower for the hand-harvested samples (36.2%) than for the grab samples obtained from the cotton picker (37.3%) when ginned on the 10-saw gin in 2019 (Table 3, Table 7). However, when hand-harvested samples were compared between the two gin types in 2019 only, 32 genotypes had significantly higher gin turnout percentage on the roller gin than on the saw gin (Table 7). Armijo and Gillum (2007) reported similar results for an upland cultivar that had significantly higher gin turnout on two types of roller gin than on a saw gin. Although more than half of the Pima genotypes showed a significant difference between ginning method in 2019, upland checks did not differ between ginning methods (Table 7).

4 | CONCLUSIONS

Although several Pima genotypes performed adequately in the field, lint yields were substantially lower than for the upland checks. The Upland checks represent two of the top performing and most popular upland cultivars in the southeast United States accounting for 3.3% (Phytogen 444WRF) and 35.6% (Deltapine 1646B2XF) of the US cotton crop in 2019 (USDA–Agricultural Marketing Service, 2019). Hence, although the Pima genotypes yielded less, it is important to note that they were compared with two commercial Upland genotypes that are well adapted and widely cultivated in the southeast United States. As expected, the majority of the Pima genotypes had significantly better fiber length and strength than the upland checks. Bleak Hall, an accession that was once grown in Charleston, SC, had the longest fibers of all genotypes in both years of the study but yielded the least. Although the Pima genotypes appeared to have much better fiber quality than the upland checks, many failed to meet the minimum requirements to avoid discounted fiber quality for Pima cotton in the United States, suggesting a lack of adaptation to the southeast United States. However, fiber quality was improved in 2019 when more optimum weather conditions existed as opposed to the harsh weather conditions of the 2018 growing season. Additional research on the adaptation of Pima cotton to the southeast United States may show further improvements in fiber quality when it is grown under more favorable growing conditions.

Ginning method appeared to have little effect on fiber length and strength, but did show many significant differences for gin turnout percentage and micronaire, with the majority of the genotypes having increased values on the roller gin than on the saw gin. However, in 2019, all Pima genotypes (excluding Bleak Hall) met the minimum requirement (3.5) for micronaire to avoid discounted fiber quality when ginned by either ginning method, indicating that roller ginning may not be necessary to preserve the fiber quality of Pima cotton produced in the southeast United States. However, it is important to note that the gins used in this study were research-type gins and had the samples been ginned by commercial-sized roller and saw gins, more differences in fiber quality may have been recognized. In future studies, it may be beneficial to assess the effects of ginning method on fiber quality by ginning on commercial gins.

Although yields were low for the Pima genotypes, this study was an informative initial step in the direction of reintroducing Pima cotton production back into the southeast United States. However, more research is needed to determine if Pima cotton production can be economically feasible in the southeast United States. This study allowed the identification of several promising Pima genotypes with adequate yield performance and fiber quality for use in breeding studies aimed at developing new Pima breeding lines with southeast US adaptation and/or improving the fiber quality of upland cotton.

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AUTHOR CONTRIBUTIONS

Sarah K. Holladay: conceptualization, formal analysis, investigation, methodology, writing—original draft. William C. Bridges: formal analysis, methodology, software, writing—review and editing. Michael A. Jones: conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing—review and editing. Todd Campbell: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing—review and editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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