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Evaluating Within-Plant Variability of Cotton Fiber Length and Maturity

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ABSTRACT

Previous studies have indicated differences in fiber quality parameters including fiber length and maturity within the canopy of cotton (*Gossypium hirsutum* L) plants. A 3-yr study was conducted to investigate the impact of within-plant variability on fiber length and maturity of upland cotton cultivars widely grown on the High Plains of Texas. Twelve upland cotton cultivars were grown in a randomized complete block design with three field replications, in Lubbock, TX, during the 2012, 2013, and 2014 growing seasons. A box-picking harvesting method was used to individualize samples so that the within-plant variability of cotton fiber quality could be studied. Bolls harvested from different positions on the plants were ginned with a table-top roller gin to minimize fiber damage. The lint from each fruiting position was blended with a supple needles laboratory blender to reduce within-sample variability while minimizing fiber breakage. Each sample collected from a different fruiting position on the plant was tested on the Advanced Fiber Information System (AFIS) with three replications of 3000 fibers. The results indicated that cultivars such as FM 9170 B2F, NG 4111 RF, PHY 499 WRF, and FM 2484 B2F showed lower within-plant variability, while DP 1044 B2RF, PHY 367 WRF, and ST 5458 B2F showed relatively high within-plant variability for AFIS fiber length and fiber maturity. In conclusion, variations in within-plant fiber length and maturity among upland cotton cultivars could be a potential source of variability for breeding programs aimed at improving fiber quality.

Core Ideas

- Cultivars showed differences for the within-plant fiber length and maturity.
- Some cultivars exhibited relatively stable within-plant fiber length and maturity.
- Genetic component plays a significant role for the differences among the cultivars.

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During the past two decades, international demand for high cotton fiber quality has increased because of the dominance of ring-spun yarn production. We hypothesized that minimizing the variability of cotton fiber quality among fibers within-bale could contribute to better spinning performance and yarn quality resulting in a better end-product with a lower cost of production. The variability in physical attributes among cotton fibers within a bale has been shown to affect textile manufacturing efficiency and the quality of the finished textile products (Smith and Cothren, 1999; Krifa, 2012). Cotton fiber quality is naturally variable within a single seed, within a single boll, within the plant, and within the field. These sources of variability in fiber quality contribute to within-bale fiber-to-fiber variability. One of the potential strategies to minimize the variability of fiber quality among fibers within a bale of cotton is to optimize the within-plant variability of cotton fiber quality.

Within-plant variability of cotton fiber quality is determined by many factors, including the growth habit of the cotton plant, genetics, and environmental conditions during cotton fiber development (Stewart, 1975; Faulkner et al., 2011; Kothari et al., 2015). The indeterminate fruiting habit of the cotton plant provides a significant source of within-plant variation in cotton fiber quality. American upland cotton is a highly indeterminate, perennial plant, which is grown in an annual cropping system (Lewis, 2002; Oosterhuis and Cothren, 2012). Cotton plants set flowers in a predictable pattern. Along the main axis, the setting of flowers occurs at the same fruiting position in 3-d intervals. Bolls set at each position along a single fruiting branch are set approximately 6 d apart (McClelland, 1916; Lewis, 2002). Three days after the first flower sets in position one, the first position boll on the next vertical node sets (Meredith and Bridge, 1973). This pattern is used for estimating relative differences in boll ages (Baker and Baker, 2010).

Cotton plants set the first position bolls at the bottom parts of the plants early in the season compared to bolls setting at the apical and distal positions. Bolls sets in the lower half of the plant and first fruiting position bolls have more time and resources to develop mature fibers. Under limited resources,

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Abbreviations: AFIS, Advanced Fiber Information System; L (n) [mm], length by number in millimeter; MANOVA, multivariate analysis of variance; CDA, canonical discriminant analysis.

bolls set at the top parts of the plants do not have access to the same amount of nutrients and water as bolls set lower on the plant. This results in differences in fiber development. Ashley (1972) reported that fruits produced at the top canopy position likely receive less carbohydrate because they are initiated late in the growing season. Also, Feng et al. (2011) reported that different seeds within a boll produce different fiber quality. Management practices such as planting date (Davidonis et al., 2004), plant population (Bednarz et al., 2006), and irrigation rate (Feng et al., 2010) can influence specific canopy positions and the within-canopy distribution of fiber properties in a cotton plant. These differential growth conditions will likely contribute to the within-plant variability of cotton fiber quality. Therefore, the indeterminate growth habit of cotton plants is one of the most important contributors to the within-plant variability of cotton fiber quality.

Additionally, growth conditions have an impact on the within-canopy variation of fiber quality, in particular on fiber maturity distribution (Ritchie et al., 2004; Feng et al., 2011). Fiber maturity is one of the most important fiber quality parameters as it has a potential impact on different fiber properties including fiber length, strength, the linear density of fiber or fineness, and other yield components such as cotton fiber density (Ayele et al., 2017). Hequet et al. (2006) suggested that when conditions are optimal during plant growth, most of the fibers could reach their full maturity level, while fibers developing under less optimum conditions will not reach full maturity. Particularly, fibers contributed by the top of the plant tend to be less mature. Immature fibers with poorly developed secondary cell walls are weak and have the propensity to break more easily during mechanical processing (Hequet et al., 2006; Abidi and Hequet, 2006; Ayele et al., 2017), creating high short fiber content that leads to more fiber-to-fiber variability within a bale of cotton. Kelly et al. (2015) suggested that fiber quality is at its best before the boll opens. Once the boll opens, the environment and mechanical processes used to transform the fiber into an industrial raw material have the potential to damage, weaken, and break fibers contributing to increased short fiber content. Unless the short fibers are removed by combing, the resulting ring-spun yarns may exhibit excessive defects. Therefore, a high combing ratio is required, leading to an elevated amount of combing noils. A high percentage of combing noils constitutes a significant cost to the textile manufacturer, hindering the use of such cotton to produce high-quality yarns.

To tackle the problem of fiber-to-fiber variability within-bale, understanding the within-plant variability of fiber quality is crucial. Several studies have reported that lint produced at a distal position relative to the main apical node tends to have lower fiber quality (Bernhardt et al., 1986; Davidonis et al., 2004; Kothari et al., 2015). It could have an impact on the fiber-to-fiber variability of fiber quality within a bale (May and Jividen, 1999; Bauer et al., 2009), and ultimately on yarn quality. However, little is known regarding the extent of within-plant variability of cotton fiber quality among genetically diverse upland cotton cultivars. The main hypothesis in this study is that within the popular cultivars widely grown on the Texas High Plains, some upland cotton may exhibit relatively stable within-plant variability of fiber quality, which offers the potential to minimize the negative impact of the distal and apical parts of the cotton plant. This study will provide insight to help develop cultivars with the optimum within-plant variability of cotton fiber quality that could potentially fit the stripper harvesting system. Therefore, the objective of this study is to evaluate the extent of within-plant variability of fiber length and maturity of 12 upland cotton cultivars popular in the Texas High Plains.

MATERIALS AND METHODS

Plant Materials, Field Design, and Agronomic Practices

Field trials were conducted in 2012, 2013, and 2014 at Quaker Farm, Lubbock County, Texas, on a loam soil. The Quaker Farm is located at 33°41′ N, 101°54′ W, the elevation is 992 m (3256 ft) above sea level, and the mean annual rainfall is 472 mm. Twelve upland cotton cultivars (PHY 367 WRF, FM 2989 GLB2, DP 1044 B2RF, NG 4010 B2RF, AT EPIC RF, NG 4111 RF, PHY 499 WRF, FM 2484 B2F, NITRO 44 B2RF, ST 5458 B2F, DP 1219 B2RF, and FM 9170 B2F) were selected for this study. These cultivars present a wide range of AFIS fiber properties (Table 1). Planting was performed in a randomized complete block design with three field replications under drip irrigation. The size of each plot was 9.1 m long and eight rows wide (7.7 m). Plants were thinned to three to four plants per foot to facilitate fruit set and proper fiber quality development. In 2012, cotton was planted on 21 May and harvested on 19 November. The total rainfall from 1 May 2012 to 30 Nov. 2012 was 129 mm. The warmest and drier weather conditions were recorded in 2012 growing season. In 2013, cotton was planted on 17 June and harvested on 25 October. Rain from 1 May 2013 to 30 Oct. 2013 totaled 204 mm. That year, cotton was planted late due to drought. Also, cotton was harvested early due to an early freeze. In 2014, cotton was planted on 19 May and harvested on the 16 November. Seasonal rainfall from 1 May 2014 to 30 Nov. 2014 totaled 456 mm. All in-season agronomic inputs such as applications of herbicide, insecticide, fertilizer, growth regulators and irrigation were performed in accordance with the best agronomic practices typical for Lubbock County. Water deficit was minimized with drip irrigation in all studies.

Table 1. Fiber properties of the selected upland cotton cultivars.

Cultivars	Maturity ratio	Length (*n*)	SF (*n*)	Fine
	no. unit	mm	%	mg/km
AT Epic RF	0.88	22.8	18.94	164.2
DP 1044 B2RF	0.87	21.6	22.84	163.8
DP 1219 B2RF	0.88	22.1	23.94	151.4
FM 2484 B2F	0.90	23.0	20.59	156.0
FM 2989 GLB2	0.90	22.5	20.84	157.3
FM 9170 B2F	0.89	22.8	20.64	150.6
NG 4010 B2RF	0.91	23.1	18.16	168.5
NG 4111 RF	0.91	23.0	17.26	168.3
Nitro 44 B2RF	0.88	23.7	18.95	152.0
PHY 367WRF	0.89	22.1	20.93	163.3
PHY 499 WRF	0.90	22.9	18.79	168.8
ST 5458 B2F	0.90	22.0	21.73	167.8

Box Picking, Ginning, and Blending

The within plant distribution of fiber quality for each cultivar was captured using a box picking harvesting method following Bednarz et al., 2006; Feng et al. (2011); and Ayele et al. (2017). The grid box divides cotton bolls by main-stem node and fruiting positions. Box with vertical orientation indicates nodes, while the horizontal orientation indicates fruiting positions. Plants from three random 1-m segments (approximately 30 plants per plot) of eight harvestable rows were removed from the field to determine within-plant fiber properties. Each boll on the individual plants was harvested and separated by node and position into the grid box. The seedcotton samples from each location on the plant were bagged by node and position. Samples were transported to the Fiber and Biopolymer Research Institute (Lubbock, TX), where they were conditioned for a minimum of 72 h at 20±1°C and 65±2% relative humidity.

Seedcotton samples from individual fruiting sites were weighed and ginned separately with a tabletop roller gin (Dennis Manufacturer, Athens, TX). To improve the homogeneity of the lint samples and facilitate testing, lint from all samples was blended on a tabletop laboratory supple needle blender. After blending, fiber quality for the lint produced at individual positions was determined with the AFIS. The AFIS measurements were averaged over three replications of 3000 individual fibers per sample. The AFIS evaluates within-sample cotton fiber properties including fiber maturity, fiber length, fineness, and neps counts. This research emphasizes the study of the within-plant variability of mean fiber length by number and fiber maturity. Cotton fiber maturity is the degree of secondary cell wall thickening relative to the perimeter and is represented by θ (theta) (Peirce and Lord, 1939; Lord, 1981). Maturity ratio is directly related to the degree of cell wall thickening. The value of theta is very small for immature fibers. However, the value of theta approaches unity when the fiber is mature (Hequet et al., 2006). High levels of fiber maturity could result in a better ability of the fibers to withstand the forces exerted during mechanical processing. Thereby, preserving fiber length. Both fiber maturity and fiber length are important fiber quality parameters and are expected to contribute to yarn quality.

Statistical Analysis

Multivariate response analysis was used to quantify the variability of within-plant fiber quality among cultivars. The results of this study show that seedcotton samples collected from the first fruiting position, node 6 through 15, account for about 77% of the total yield per plant. The remaining 20% plus is contributed by bolls from the second, third, and vegetative branches. The numbering of the nodes begins with the cotyledon node as number 1. Fruiting branches are reproductive branches on which bolls develop, while fruiting position refers to the order in which bolls are produced on a fruiting branch. Nodes are the location on the main stem where fruiting branches or vegetative branches arise (Jenkins et al., 1990). Only the first position nodes 6 through 15 (no missing data) were considered to evaluate the within-plant variability of fiber length and maturity.

In the multivariate response analysis, cultivar, year and cultivar × year interactions were considered as independent variables while fruiting branches were considered as a dependent (response) variable. JMP Pro 12 Software, Statistical Discovery from SAS, was used to analyze the within-plant variability of cotton fiber quality among the cultivars. When performing a multiple group discriminant analysis, the JMP Pro software fit model automatically determines the canonical components that discriminate between categorical variables. The maximum number of canonical axes could be equal to the number of groups minus one, or the number of variables in the analysis, whichever is smaller (SAS Institute, 1999). In this analysis, canonical discriminant analysis (CDA) was used. The CDA axes are linear combinations of variables that maximally discriminate the structure between the treatments (Kelly et al., 2015). The multivariate response analysis generates eight different canonical axes, for the 12 upland cotton cultivars, while two canonical axes were generated for the three growing seasons of selected important cotton fiber properties such as maturity ratio and AFIS mean length by number. In this data analysis, the first two canonical axes were considered to explain the within-plant variability of fiber quality among the 12 upland cotton cultivars. The first canonical axis explains the maximum variability. The second canonical axis explains the remaining variability independently. Note that the canonical discriminate analysis space is larger than the selected two main axes (canonical axis 1 and 2). As the objective of this analysis is to show the differences between the cultivars for the within-plant fiber quality, only those canonical axes that significantly maximize the distance between individual cotton cultivars were chosen. Thus, the remaining axes that do not explain a significant part of the within-plant fiber quality among the cultivars were not considered.

RESULTS AND DISCUSSION

Variation in mean length by number and mean fiber maturity were characterized across positions that produced a boll for every cultivar. Multivariate statistical techniques were used to isolate the portion of this variation in fiber quality attributed to the environment (year) and the portion of the variation in fiber quality attributed to cultivar. Within-plant variation in mean fiber length was considered first, followed by a variation in fiber maturity.

Within-Plant Variability of Advanced Fiber Information System Mean Length by Number

Production year had a significant impact on the distribution of fiber length within the plant (Table 2). The significant interaction term (year × cultivar) suggests the within-plant distribution of fiber length depends on both the year and cultivar. Thus, even if the cultivar term did not meet the minimum threshold for significance ($\alpha = 0.05$), there is significant variation in the distribution of fiber length by number within the plant across cultivars. While the MANOVA reveals that production year and cultivar have a significant impact on the within-plant distribution of fiber length (Table 2), it does not characterize the nature of how this distribution varies across years. Thus, canonical scores identifying maximal differences between groups in the multivariate response analysis were used to quantify significant differences in the within-plant distribution between years and cultivars in each growing season.

Table 2. Multivariate analysis of variance for the within-plant variability of mean length by number for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

Sources of variation	Score	Approximate *F*	Numdf	Dendf	*P* > *F*
Year	0.29	6.06	18	128	<0.0001***
Cultivar	0.19	1.23	99	462	0.086ns†
Cultivar × year	0.05	1.25	198	554	0.0254*

* Significant difference at 0.05.

*** Significant difference at 0.0001.

† ns = Nonsignificant.

Variation in Within-Plant Advanced Fiber Information System Mean Length by Number across Growing Seasons

The centroids of the length scores for each production year plotted over the canonical axes reveals that 2012 and 2014 capture the largest difference in the within-plant distribution of fiber length across years (Fig. 1). The year 2012 has the highest score on the canonical axis characterizing the largest difference in the distribution of fiber length, and 2014 has the lowest score. Years 2012 and 2013 capture the largest difference across the second axis of variation (Fig. 1). While the within-plant distribution of fiber length for 2012 and 2014 are very different from the primary axis of variation, the centroid scores of these 2 yr are very similar along the second axis.

As shown in Fig. 1, the distributional differences in within plant fiber length captured by the first canonical axis are best characterized by the differences between 2012 and 2014. The average length of fiber produced at nodes 6 to 9 is similar across 2012 and 2014, with slightly longer fibers produced in 2013. However, fiber length is not distributed the same at higher nodes in 2012 and 2014. While fiber length is relatively stable across all nodes of the first position fruits in 2014, fibers are more than 3 mm shorter (nearly one-eighth of an inch) at higher nodes in 2012 (Fig. 2).

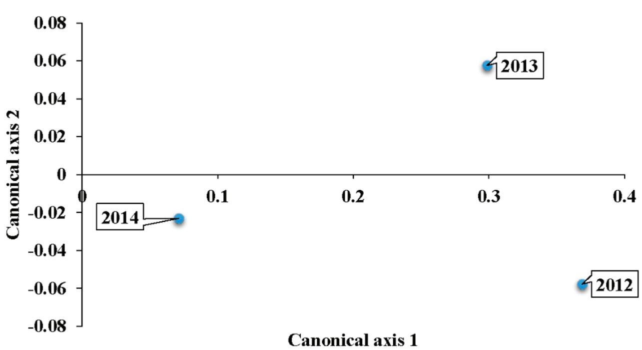

Fig. 1. Variation of within-plant fiber length by number across the year on the first and second canonical axes for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

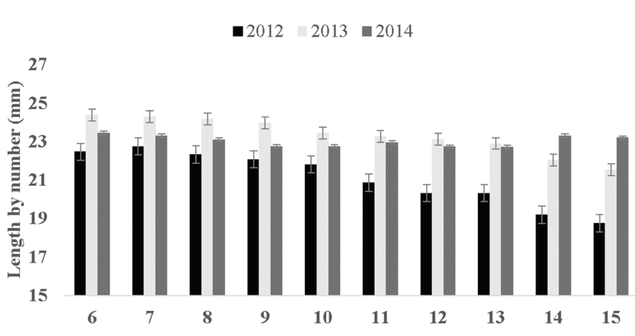

Fig. 2. Within-canopy distribution of mean fiber length by number across the year for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

The second canonical axis characterizes the remaining portion of variation in the distribution of fiber length within the plant among years. Thus, 2012 and 2013 sit at the extremes of the second canonical axis (Fig. 1) which explains variations in within-plant fiber length across the years. Although fiber lengths tend to decline at higher nodes for both years, the most noticeable drop in length begins at a lower node (Node 11) in 2012 in comparison with 2013 (Node 13) as shown in Fig. 2. Additionally, fibers produced at each node are shorter in 2012 compared with the 2013 growing season, which could contribute to the largest variation captured by the second canonical axis. It appears the warmest and drier weather conditions recorded in the 2012 growing season may have affected fiber elongation during the fiber development stage at each fruiting position.

Variation in Within-Plant Advanced Fiber Information System Mean Length by Number Among Cultivars

The distribution of fiber length within the plant depends on the cultivar and the year. Because of the significant year × cultivar interaction, the analysis of the distributional differences across cultivars was separated by year.

Within-Plant Variability of Length by Number Among Cultivars in 2012

While the primary canonical axis characterizes the primary source of variation in within-plant fiber length between cultivars, it does not reveal clustering, or similarities, within groups of cultivars in 2012 (Fig. 3). The cultivar DP 1044 B2RF scored the highest on the primary canonical axis, while the lowest scoring

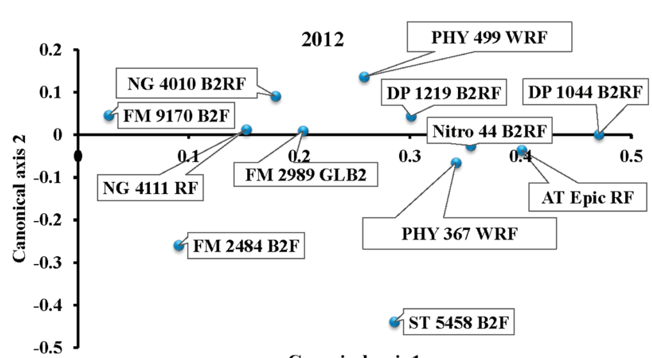

Fig. 3. Canonical discriminate analysis for the within-plant variability of Advanced Fiber Information System mean length by number for 12 upland cotton cultivars grown in 2012.

was FM 9170 B2F. On the second axis of variation, the cultivar PHY 499 WRF scored the highest and ST 5458 B2F scored the lowest. Scores for most cultivars along the second axis clustered closer to PHY 499 WRF, while scores for FM 2484 B2F fell between the cluster of cultivars and ST 5458 B2F.

Within-Plant Variability of Length by Number Among Cultivars in 2013

The scores of the within-plant distribution of fiber length did not reveal any clustering in 2013. Scores of the cultivars FM 2484 B2F and NG 4111 RF sit at the extremes of the primary axis, while DP 1044 B2RF and AT Epic RF are sitting at the extremes of the second canonical axis (Fig. 4). However, the scores for DP 1044 B2RF was not different from FM 2484 B2F and FM 2989 B2F on the primary axis, while it is different from NG 4111 RF both on the first and second canonical axis of variations.

Within-Plant Variability of Length by Number Among Cultivars in 2014

In 2014, DP 1044 B2RF and ST 5458 B2F scored much higher than other cultivars along the primary axis, with DP 1044 B2RF having, the highest overall score (Fig. 5). The lowest scoring cultivars along the primary axis were PHY 499 WRF and FM 2484 B2F. While these two cultivars were similar in terms of the primary axis, they exhibited different scores along the second axis. While they sit at extremes of the primary canonical axis, DP 1044 B2RF and PHY 499 WRF are similar along the second canonical axis. Thus, PHY 499 WRF and DP 1044 B2RF were selected to characterize the within-plant variation in fiber length captured by the primary axis of variation in the within-plant distribution of fiber length.

In summary, some cultivars consistently score low across the two major axes used to evaluate the within-plant variability of fiber length among the cultivars. For example, NG 4111 RF consistently grouped with the low scoring cultivars while DP 1044 B2RF was consistently grouped with the high scoring cultivar across the study period. The distribution of fiber length within the canopy for NG 4111 RF was shown to be stable across nodes in all growing season suggesting that cultivars with a similar score to NG 4111 RF will produce a more stable within plant distribution of fiber length. FM 9170 B2F and PHY 499 WRF were among the lowest scoring cultivars in both the 2012 and 2013 growing seasons. Conversely, the distribution of fiber length within the canopy of DP 1044 B2RF was shown to be less stable as revealed by its high canonical scores each year.

Cultivars such as DP 1044 B2RF, PHY 367 WRF, and ST 5458 B2F were among the highest scoring in all production years and produced less stable within-canopy length distributions. The fiber produced at nodes within the canopy of ST 5458 B2F and PHY 367 WRF were more like the pattern seen in DP 1044 B2RF during the study period, where higher nodes tend to produce shorter fibers throughout the nodes considered.

Table 3 shows the ranking of cultivars based on the first and second canonical scores mean comparisons. In 2012, DP 1044 B2RF, AT Epic RF, DP 1219 B2RF, Nitro 44 B2RF, PHY 499 WRF, and ST 5458 B2F are high scoring cultivars. These cultivars showed high within-plant variability for mean fiber length. FM 9170 B2RF, FM 2484 B2F, NG 4111 RF, NG 4010 B2RF, and FM 2989 GLB2 are low scoring cultivars suggesting that these cultivars show less within plant variability in fiber length. In all growing seasons, DP 1044 B2RF shows high within-plant variability characterized by higher scores on the first canonical axis (Table 3). Some cultivars showed different rankings each year. For example, DP 1219 B2RF and AT Epic RF are grouped in the higher-ranking cultivars in both 2012 and 2013 while they are grouped in low ranking cultivars in 2014. As mentioned earlier, 2012 and 2013 are characterized by low precipitation and variable weather conditions. Favorable growth conditions were recorded in 2014. It appears that some cultivars are more sensitive to the changes in environmental conditions while others are less sensitive. Conversely, some cultivars showed similar ranking in each growing season. DP 1044 B2RF and ST 5458 B2F consistently ranked with higher scoring cultivars and did not show improvement even with favorable growing conditions. This could have an impact on within-plant fiber quality variation of fiber length and maturity. The within-plant variability captured by the second canonical was significant in 2012 and 2013, while no significant difference was observed among the cultivars in 2014.

To demonstrate variation in fiber length across the main-stem node, two cultivars in each growing season were selected based on the score value and locations on first and second canonical axes. Because they sit at extremes of the first canonical axis and are at similar levels on the second canonical axis (Fig. 4), differences in DP 1044 B2RF and FM 9170 B2F were used to characterize the largest source of significant variation in the

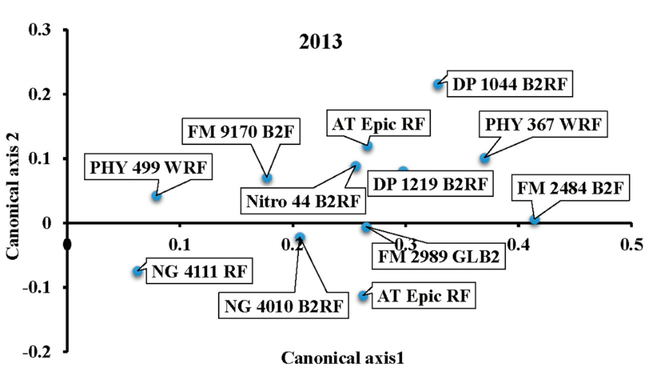

Fig. 4. Canonical discriminate analysis for the within-plant variability of Advanced Fiber Information System mean length by number for 12 upland cotton cultivars grown in 2013.

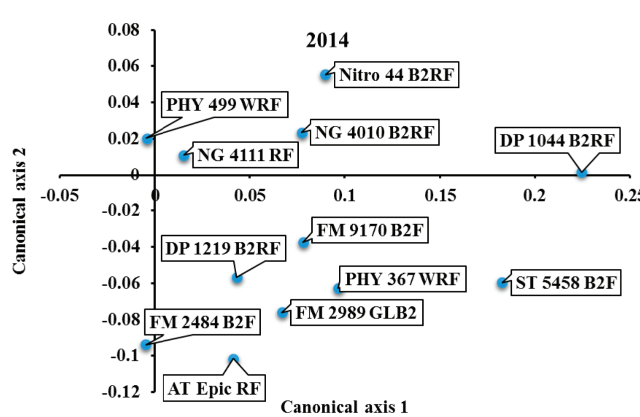

Fig. 5. Canonical discriminate analysis for the within-plant variability of Advanced Fiber Information System mean length by number for 12 upland cotton cultivars grown in 2014.

Table 3. Variation of within-plant fiber length by number based on rankings of first and second canonical scores for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

Cultivars	Scores of canonical axis 1			Scores of canonical axis 2		
	2012	2013	2014	2012	2013	2014
AT Epic RF	0.401ab†	0.266abc	0.042c	–0.036a	0.120ab	–0.102a
DP 1044 B2RF	0.471a	0.329ab	0.225a	0.001a	0.216a	0.002a
DP 1219 B2RF	0.301abcd	0.298ab	0.043c	0.044a	0.080abc	–0.057a
FM 2484 B2F	0.091de	0.414a	–0.005c	–0.260bc	0.006abc	–0.094a
FM 2989 GLB2	0.203bcde	0.262abc	0.067bc	0.009a	–0.112c	–0.076a
FM 9170 B2F	0.028e	0.177bcd	0.078abc	0.046a	0.071abc	–0.038a
NG 4010 B2RF	0.179bcde	0.206bcd	0.077bc	0.090a	–0.022bc	0.023a
NG 4111 RF	0.152cde	0.062d	0.015c	0.012a	–0.075bc	0.011a
Nitro 44 B2RF	0.355abc	0.255bcd	0.090abc	–0.026a	0.089abc	0.055a
PHY 367 WRF	0.342abc	0.370ab	0.096abc	–0.066ab	0.101ab	–0.063a
PHY 499 WRF	0.258bcde	0.079cd	–0.004c	0.136a	0.043abc	0.020a
ST 5458 B2F	0.286abcd	0.265abc	0.183ab	–0.439c	–0.006bc	–0.060a

† Means followed by the same letter within a column are not significantly different (P = 0.05).

distribution of within-plant fiber length across cultivars in 2012. The within plant distribution of fiber length for FM 9170 B2F is stable from nodes 7 to 11 (Fig. 6). The fiber length for FM 9170 B2F does not begin to drop until after this node. However, the within-plant distribution of fiber length for DP 1044 B2RF is not stable at any point. In this study, some cultivars showed similar types of fiber properties across fruiting branches. Except node 12, the fiber produced at higher nodes are shorter from node 7 to the upper nodes of DP 1044 B2RF. It appears the dry period in 2012 may have affected more fiber elongation of DP 1044 B2RF than FM 9170 B2F.

A change of rank is also observed among several cultivars (Table 2). While the cultivar NG 4111 RF had the third lowest score in 2012, it had the lowest scores in 2013. FM 2484 B2F was the second lowest scoring cultivar in 2012, while it was the highest scoring cultivar in 2013 (Fig. 3). It appears that FM 2484 B2F scored high for fiber length in 2013 as it produced the longest fibers in the lower part of the plant compared to its higher nodes that could contribute to within-plant variability in length. In 2013, the cultivars FM 2484 B2F F and NG 4111 RF sit at the extremes of the primary axis of variation (Fig. 4). The length produced at nodes 6 to 12 in NG 4111 RF was more stable than lengths produced at higher nodes. FM 2484 B2F produced relatively stable and longer fibers between nodes 6 through 9 as compared to NG 4111 RF, while NG 4111 RF produced relatively longer fiber in the middle of the canopy (nodes 10 through 12) and then showed a declining trend from node 12 toward the upper nodes. In 2013, FM 2484 B2F showed a declining trend in mean fiber length by number from an average of 26 to 21 mm across the selected fruiting branches (Fig. 6).

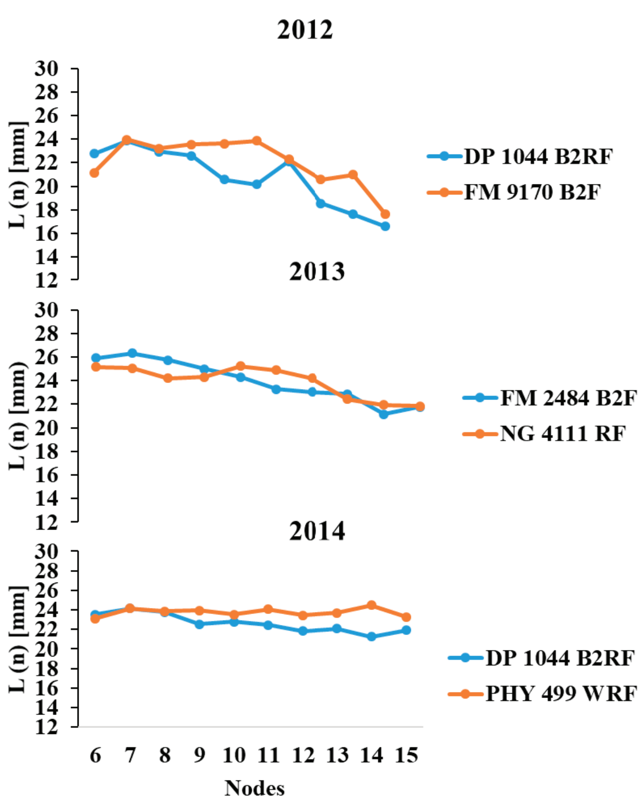

Fig. 6. Variations in fiber length across main-stem nodes of selected upland cotton cultivars in 2012, 2013, and 2014.

As in 2012 and 2013, fiber lengths produced by DP 1044 B2RF at higher nodes were shorter on average. The longest fibers (mean fiber length by number) were produced at node 7, averaging about 23.9 mm, and the short fibers were produced at node 14, averaging around 22.5 mm. However, in 2014, PHY 499 WRF exhibited one of the most stable within plant distributions of fiber length. There is no noticeable drop in fiber length produced at higher nodes for PHY 499 WRF in 2014. As compared to DP 1044 B2RF, except for the first few nodes, PHY 499 WRF produced longer fibers in most selected parts the plant, which contributed to the within-plant fiber length variation among cultivars (Fig. 6).

Within-Plant Variability of Advanced Fiber Information System Fiber Maturity

The multivariate analysis indicated that the growing seasons and cultivars have a significant impact ($P < 0.05$) on the variation of within-canopy fiber maturity. No significant difference was observed for the year × cultivar interaction, suggesting that the performance of different cultivars in each year was the same for the within-plant variability for fiber maturity (Table 4). To describe the nature of within-plant variability of fiber maturity across years and among cultivars, canonical scores that identify the maximum differences between groups in the multivariate response analysis were used.

Table 4. Multivariate analysis of variance for the within-plant variability of maturity ratio for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

Sources of variation	Score	Approximate *F*	Numdf	Dendf	*P* > *F*
Year	0.205	0.205	18	128	<0.0001***
Cultivar	0.165	0.165	99	462.8	0.0192*
Cultivar × year	0.051	0.051	198	554.6	0.0578ns†

*Significant difference at 0.05.
***Significant difference at 0.0001.
† ns = Nonsignificant.

Variation in Within-Plant Fiber Maturity among Growing Seasons

The canonical scores across growing seasons plotted over the canonical axes capture the largest differences in the within-plant distribution of fiber maturity across years. The maximum variation of fiber maturity observed across the fruiting branches during the three growing seasons was captured by the first canonical axis as illustrated in Fig. 7. The results revealed that 2012 and 2014 capture the largest difference in the within-plant distribution of fiber maturity across years. The highest score on the main canonical axes was recorded for the year 2012, suggesting that this growing season characterizes the largest differences for the within-canopy distribution of fiber maturity. The lowest within-canopy variability of fiber maturity was observed in 2014 as indicated by the lowest centroid score, while years 2012 and 2013 capture the largest difference across the second canonical axis (Fig. 7). Although 2012 and 2014 show the maximum difference in the within-plant distribution of fiber maturity on the primary axis, the centroid scores of the 2 yr are very similar along the second canonical axis.

As in the within-canopy distribution of fiber length shown in the previous section, the distributional differences in within-plant maturity captured by the first canonical axis are best described by the 2012 and 2014 growing seasons. The average fiber maturity produced across nodes 6 to 10 was relatively stable for the year 2012 and 2014, with more immature fibers produced in 2014. Nevertheless, fiber maturity was not distributed the same at higher nodes. As illustrated in Fig. 8, after node 10, a declining trend was observed in 2012, while relatively stable within-canopy fiber maturity was recorded in 2014.

Although the second canonical axis was expected to characterize a small portion of the variation, it captured the largest difference in within-plant fiber maturity for the years 2012 and 2013. As illustrated in Fig. 7, years 2012 and 2013 sit at the extremes of the second canonical axis. The fiber maturity tends to decline in the uppermost nodes of a cotton plant in both 2012 and 2013 production years. The most noticeable drop in maturity begins at node 11 in 2012 and at higher node (Node 13) in 2013, which may contribute to the within-plant variability among the cultivars.

Variation in Within-Plant Fiber Maturity Among Cultivars

The canonical discriminate analysis revealed that although the growing seasons have a significant effect on the within-plant variability of fiber maturity, the distribution of fiber maturity within the plant also depends on the cultivars. The primary canonical axis characterizes the primary source of variation of the within-plant fiber maturity between cultivars. As observed in the within-canopy distribution of fiber length, the cultivar DP 1044 B2RF exhibited the highest score on the primary canonical axis of fiber maturity, while the lowest score was recorded for FM 9117 B2RF (Fig. 9). On the second axis of variation for the within-canopy distribution of fiber maturity, the cultivar FM 2484 B2F scored the lowest, and PHY 367 WRF scored the

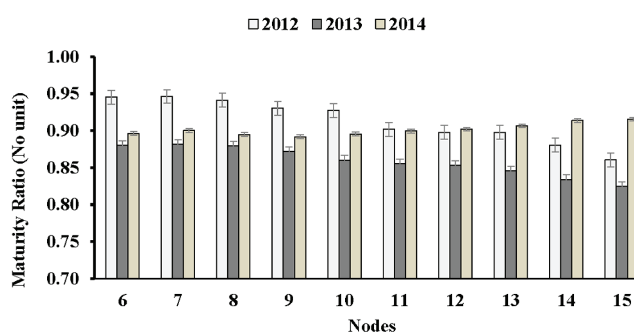

Fig. 8. Variation of fiber maturity across fruiting branches of 12 upland cotton cultivars grown in 2012, 2013, and 2014.

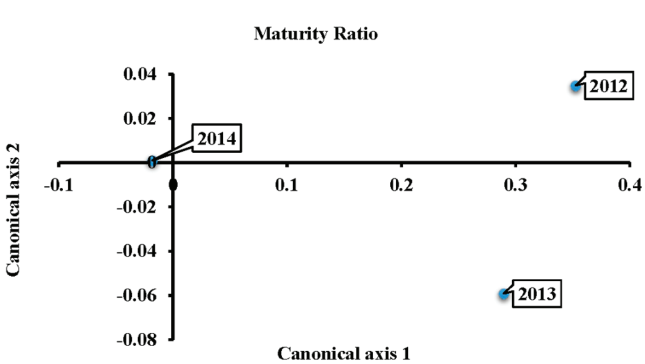

Fig. 7. Canonical discriminant analysis for the effect of year on within-plant maturity ratio for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

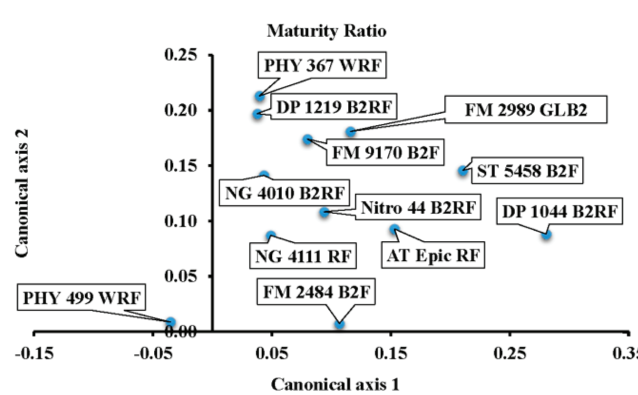

Fig. 9. Canonical discriminant analysis of within-plant variability of fiber maturity for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

Table 5. Variation of within-plant fiber maturity based on rankings of first and second canonical scores for 12 upland cotton cultivars grown in 2012, 2013, and 2014.

Cultivars	Canonical axis 1 scores	Canonical axis 2 scores
AT Epic RF	0.153abc†	0.093ab
DP 1044 B2RF	0.281a	0.088ab
DP 1219 B2RF	0.038cd	0.197a
FM 2484 B2F	0.107bcd	0.007b
FM 2989 GLB2	0.116bc	0.181a
FM 9170 B2F	0.080bcd	0.174a
NG 4010 B2RF	0.043cd	0.141ab
NG 4111 RF	0.049cd	0.087ab
Nitro 44 B2RF	0.094bcd	0.108ab
PHY 367 WRF	0.040cd	0.213a
PHY 499 WRF	−0.035d	0.009b
ST 5458 B2F	0.210ab	0.146ab

† Means followed by the same letter within a column are not significantly different ($P = 0.05$).

highest, which is an indication of within-canopy variability in fiber maturity among the cultivars.

As for the mean fiber length by number, the first and the second axes captured the maximum variability among the cultivars for fiber maturity. Based on the mean comparisons of the first and the second canonical axes, similar cultivars were grouped for within-plant fiber maturity. DP 1044 B2F, AT Epic RF, and ST5458 B2F are high scoring cultivars (Table 5). High within-plant variability of fiber length previously discussed may be related to high within-plant variability in fiber maturity. It has been reported that less mature fibers tend to be prone to breakage when submitted to mechanical stress, creating short fibers which negatively impact mean fiber length (Kothari et al., 2015; Ayele et al., 2017).

Differences in PHY 499 WRF and DP 1044 B2RF were used to characterize the largest source of variation in the distribution of within-plant fiber maturity as these two cultivars sit at the extremes of the primary canonical axis. In this study, PHY 499 WRF was found to be the lowest scoring cultivar, while DP 1044 B2RF scores the highest on the primary axis (Table 4) representing low and high variability, respectively, in fiber maturity among the cultivars (Fig. 10). Compared to PHY 499 WRF, the trend of fiber maturity across the fruiting branches of DP 1044 B2RF tends to show a sharp decline toward the uppermost part of the plant (Fig. 10). The upper nodes of DP 1044 B2RF appear to contribute excessive immature fibers compared to PHY 499 WRF. This result agrees with Bauer et al. (2009), who compared two upland genotypes for the within-canopy variability of fiber properties. In their study, the fiber length at lower nodes (nodes 9–12) was longer compared to the top bolls.

CONCLUSIONS

In this study, different cotton cultivars exhibited variable within-canopy fiber length and maturity. In general, fibers produced at higher nodes are less mature and shorter in all cultivars considered. However, the extent of within-plant variation of fiber length and maturity within a canopy is significantly different across cultivars. While some cultivars consistently produced shorter and less mature fibers at higher nodes, many cultivars tended to have a more stable within plant distribution of fiber

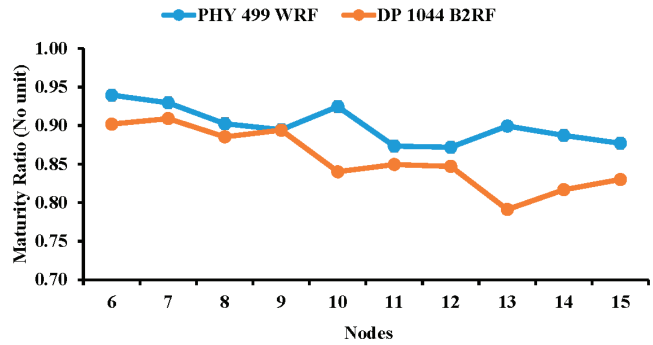

Fig. 10. Variation in within-plant maturity ratio (no unit) for DP 1044 B2RF and PHY 499 WRF grown in 2012, 2013, and 2014.

length and maturity before a drop in these fiber properties. Cultivars such as FM 9170 B2F, NG 4111 RF, and PHY 499 WRF tended to produce a more consistent fiber length within the canopy, while the fiber length produced within the canopy of DP 1044 B2RF, ST 5458 B2F, and PHY 367 WRF were more variable across years. The results of the multivariate response analysis revealed that cultivars with lower scores on the two canonical axes tended to have more mature and longer fibers that are stable across the fruiting branches. Conversely, cultivars with high canonical scores on the main axes tended to produce highly variable within-plant fiber length and maturity. High scoring cultivars produce less mature and shorter fibers within the canopy of the plant. Cultivars with relatively stable fiber properties across the fruiting branches minimize the impact of immature fibers contributed by the top crop. Cotton cultivars that exhibit lower within-plant variability could fit the stripper harvester system commonly used on the Texas High Plains. Based on AFIS fiber properties, high variations of within-plant fiber properties were detected among upland cotton cultivars considering only the first position bolls. It appears that genetic components play a significant role in the within-plant variability of fiber quality that could be a potential source of variation for further improvement in cotton fiber quality. While longer fibers contribute to stronger and finer yarns, excessive short fibers can cause imperfections in the yarn structure. Future papers will establish and quantify the impact of the complete distribution of fiber length produced at each position.

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