COTTON YIELD COMPONENTS AND YIELD STABILITY

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Abstract

Cotton lint yields in the USA have experienced periods of annual increases and decreases in the 20th century, but yields have not increased in recent years. Recent stagnation in cotton yields has been attributed to lack of genetic diversity, climatic extremes, and possibly physiological reasons related to prevalent yield components. The purpose of this paper is to examine influences on U.S. cotton yields and make recommendations to ameliorate an apparent yield plateau.

Introduction

Chaudhry (1997) reported that U.S. cotton yields had been stagnant for the previous 17 years. Meredith (1998) proposed that the rate of yield change was negative from 1982-1996. Wessling et al. (1973) showed that weather and management practices played a significant role in year to year variations in cotton yields. Meredith (1995) indicated that genetic improvements in cotton yield peaked around 1987. Meredith's report suggested that the long-term yield trend may have been influenced by genetic factors as well as variations in weather and management practices. Lewis and Sasser (1999) analyzed the yield data of the U.S. upland cotton crops from 1960 through 1998 and determined how the rates of yield change occurred during this time period. Their analyses showed that the rate of yield improvement changed from an annual increase of about 5 pounds/acre/year in 1960 to zero increase by 1968. Then, the U.S. crop experienced annual losses in yield from 1969 through 1974. From 1975 through 1983 the yield of the crop increased each year to an average annual increase of about 15 pounds/acre/year in the mid-1980s. Since that time, the annual change in yield has decreased each year and since 1990 has actually sustained yield losses on a national annual basis. Lewis and Sasser (1999) also examined the yield data from the mid-South region and found it to be highly correlated with the national yield data. A correlation analysis between fiber quality properties and yield resulted in a good correlation between fiber length and yield. Because fiber length and strength are correlated within the upland crop, there is also a fairly good correlation between fiber strength and yield. However, no correlation was found between average crop micronaire and average crop yield. The factors that can influence cotton yield such as variety changes and other genetic factors, environmental and weather conditions, crop management practices, pest population trends, etc. should be carefully studied for the 1970-1985 period since the crop sustained steady yield increases during that time. These reports constitute significant reasons for concern as to the ability of U.S. cotton to remain competitive in global textile markets and indicate that we must re-examine our understanding of the physiological/genetic processes that influence yield.

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The purpose of the present study is to define and evaluate changes in basic yield components during the time of rapid yield improvement, i.e. 1970-1985, and compare these changes to similar events during recent years, i.e., 1985-1998, when the rate of yield improvement suffered serious reduction and became negative. The objective of this exercise is to attempt to understand the cause, or causes, of the recent decrease in the rate of yield improvement and to search for potential remedies.

Background

Cotton lint yield is probably best understood in terms of the components that make it up. Fiber or lint yield in cotton is defined by two major components, i.e., the number of seeds produced per acre and the weight of fiber produced on the seed. Cotton fibers are elongated epidermal cells of the outer integument of the seed coat. No seed - no fiber.

<u>Yield</u> = [(No. of seeds/Acre)(Weight of fiber /Seed)]

The number of seeds per acre is determined by the number of plants per acre, the number of bolls per plant, and the number of seeds per boll. This suggests that the number of seeds produced per acre may be influenced to a high degree by management and environmental factors and to a lesser extent by genetic considerations.

<u>Seeds per acre</u> = [(Plants/Acre)(Bolls/Plant)(Seeds/Boll)]

The weight of fibers per seed is a function of the number of fibers per seed and the average weight per fiber.

<u>Weight of fiber per seed</u> = [(Number of fibers per seed)(Average weight/fiber)]

From a cell physiology perspective, the number of fibers per seed is determined by the number of epidermal cells in the outer epidermis of the seed coat which initiate elongation and develop into lint fibers. Physically, the number of fibers per seed is a function of the weight of fiber per seed divided by the mean weight per fiber.

Number Of Fibers/Seed = Weight of fiber per seed/Mean weight per fiber

The mean weight per fiber is a function of the mean length of the fibers on the seed and the mean linear density of the fibers.

Average weight per fiber = (Mean fiber length)(Mean linear density of the fibers on the seed)

Physiologically, the average weight per fiber is determined by the degree and extent of primary and secondary cell wall growth. Primary wall growth is equivalent to fiber elongation. Historically, as long as a plant cell is increasing in volume it is considered to be producing primary cell wall. After a plant cell stops increasing in volume but continues to increase in weight it is thought to have entered the secondary cell wall phase of growth. Secondary wall growth is equivalent to an increase in the linear density (micronaire, tex, etc.) of the fiber or the thickness and, perhaps, the density of the secondary cell wall. Thus, the mean weight per fiber is a function, physiologically speaking, of both primary and secondary cell wall-growth. This constitutes strong evidence that the weight of fiber per seed is heavily influenced by genetic considerations, especially in so far as the number of fibers per seed is concerned.

A relatively small increase in the weight of fiber per seed may have a highly significant impact on lint yield. For example, in the south central and southeastern U.S. cotton-belt, the long-term average number of seeds per acre produced is approximately 7 million. Thus, if the weight of fiber per seed were increased by only 5 milligrams, this could result in a yield increase of a little more than 75 pounds of lint per acre.

Procedure

Yield trends were analyzed as reported by Lewis and Sasser (1999) utilizing historical yield data as reported by the National Agricultural Statistics Service, USDA. Segmental rate analyses were done by dividing the polynomial yield trend curve into overlapping segments around "bend points" that occurred between 1960-1978, 1970-1998, and 1980-1998; and calculating by least squares a polynomial equation that constituted a reasonable fit to each segment, taking the first derivative of the resulting quadratic equation, and calculating the rate of yield change from the first derivative. Rates of yield change were then plotted against the years in the overlapping segments. This procedure provided for estimates of the years when the rate approached zero, *i.e.*, the "bend points" in the polynomial describing the yield trend over the period, and the year when the rate changed direction, i.e., the year when the overlapping segments crossed.

Yield components, i.e., seeds per acre and weight of fiber per seed, were calculated for specific varieties from data contained in National Cotton Variety Tests from 1970-1996. Variations in yield components over nine locations from Florence, SC to Shafter, CA were calculated in a similar manner for national standard varieties from data contained in the 1996 National Cotton Variety Test. These calculations utilized boll size, lint percent, seed index and lint and seed yields. Estimates of the basic yield components were derived from these data. Variations in yield components over locations were then analyzed on the basis of degrees west longitude of the locations in order to generate functional mathematical relationships. Determinations of the weight of fiber per seed per pound of lint yield per acre and the number of seed per pound of lint yield per acre were accomplished by plotting the lint yield per acre against the weight of fiber per seed and the number of seeds per acre by location and variety across the nine Beltwide locations.

Results and Discussion

Figure 1 shows the relationship between the rate of yield change in mid-South upland cotton between 1970-1998. These data were developed utilizing the procedures and data published by Lewis and Sasser (1999). From the early 1970s up to the mid-1980s cotton yields were improved at an excellent rate, exceeding 20 pounds/acre/year by 1984 (Fig. 1). This is in contrast to a steadily declining rate from the mid 1980s up to 1992 when the rate of yield loss approached zero and then declined to a rate of about a minus 18 pounds per acre per year in 1998 (Fig. 1). As suggested by Lewis and Sasser (1999) this situation deserves further investigation. Whatever was going on with yields in the earlier period (1970-1985) is what we would like to have happen and whatever was going on in the later period (1985-1998) is what we would prefer not to have happen. Thus, it seems worthwhile to investigate these two time periods in an attempt to discover any significant differences that may have occurred.

The U.S. Plant Variety Protection Act was passed in 1970. This law seems to have prompted an increased input of resources into the development and release of new commercial cotton varieties, which may have contributed to the rapid increase in the rate of yield improvement in the 1970s and early 1980s. By the mid 1980s a movement was well underway in the cotton breeding industry, both private and public, directed towards the discovery of genes which could be patented and the genetic transformation of cultivated upland cotton with these patented or patentable genes. In fact, Galau (1985) published the first disclosure for patent of cultivated cotton regenerated from tissue culture. This movement was precipitated by an apparent change in policy by the U.S. Patent and Trademark Office which allowed the issue of patents on sexually reproduced plants and individual plant genes and may have diverted critical resources away from the development of new varieties into the discovery of patentable genes and transgenic varieties. One result of this change appears to have been a reduction in the development of broadly different new varieties based on segregation and recombination of the complete genomes of the parental lines (e.g., conventional breeding). Indeed, during recent years, backcross breeding of transgenic varieties has dominated the cotton breeding industry. The transgenic varieties which now control a majority of the commercial cottonseed trade are existing varieties with a patented gene inserted into the recurrent parent. These genes have focused on input traits, that is resistance to insects and herbicides and not on output traits such as yield and quality. In addition, an amendment to the U.S. Plant Variety Protection Act was passed in 1994, which added the "essentially derived" provision to the law, which appears to have greatly restricted the free exchange of germplasm among cotton breeders. The essentially derived provision of the Plant Variety Protection Act seeks to extend protection to a variety owner in which a non-owner of the same variety has substantially derived the protected variety in question through sexual or asexual means. The impact of the essentially derived clause of the Plant Variety Protection Act will not be known for some years. Its immediate impact would seem to restrict breeding with Plant Variety Protected germplasm for fear of unintentionally violating the essentially derived clause of the law.

As detailed in the "Background" section above, cotton yields are made up of two major components, i.e., the number of seeds produced per acre and the average weight of fiber produced per seed. Cotton is like most of the important field crops in that a major component of yield is the reproductive potential, or the number of seeds produced per acre. However, it differs from the other field crops in that if no fiber or a reduced amount of fiber is produced per seed the lint yield may be severely reduced. Cotton lint is the truly valuable yield component, whereas, only the number of seed produced per acre is the determining component of yield in the great majority of other field crops grown in the U.S. cotton-belt.

Benedict et al. (1999) reported that Stoneville 213 produced approximately 80 milligrams of fiber per seed. As a result of this report, and existing personal data indicating that the most popular varieties currently grown in the Delta region produce only 50-60 milligrams of fiber per seed, the weight of fiber per seed and the number of seeds per acre were calculated from data reported in the National Cotton Variety Test Delta Region for 1970, 1975, and 1985 for Stoneville 213 and DeltaPine 16, two very popular varieties in the 1970s. In addition, similar calculations for DeltaPine 50 and Suregrow 125 were made for 1990, 1992, 1993, 1994, 1995 and 1996 two very popular varieties in the 1980s-1990s era. Figure 2 shows the results of this study. These data clearly show that there was a decrease in the weight of fiber per seed and an increase in the number of seeds per acre in the 1990s era varieties as compared to the 1970s era varieties. Specifically, Stoneville 213 and DeltaPine 16 produced about 72 milligrams of fiber per seed while DeltaPine 50 and Suregrow 125 yielded approximately 60 milligrams of fiber per seed, a difference of about 12 milligrams of fiber per seed. If the number of seeds per acre is held constant at 7 million seeds per acre, a change in the weight of fiber per seed of 12 milligrams represents a potential yield change of approximately 185 pounds of lint per acre. On the other hand, the 1990s era varieties produced about 8.5 million seeds per acre whereas the 1970s era varieties produced only about 5.5 million seeds per acre. Again, a highly significant difference of about 3 million seeds per acre, or about 600 pounds of seed per acre.

Figure 3 shows these same data, however, here the two major yield components are depicted in terms of how they affect the pounds of lint yield per acre over the same time period and varieties. In this case the 1970s era varieties produce between 70 and 90 micrograms of fiber per seed per pound of lint yield per acre, whereas the 1990s era varieties produce between 46 and 60 micrograms of fiber per seed per pound of lint yield per acre. Furthermore, the 1970s era varieties produced between 6132 and 6581 seeds per acre per pound of lint per acre, while the 1990s era varieties yield between 6969 and 8528 seeds per acre per pound of lint yield per acre. These findings indicate that the 1970s era varieties relied on producing more fiber per seed in order to produce their lint yield, whereas the 1990s era varieties depend on producing more seeds per acre to obtain their lint yield.

The data shown in Figures 2 and 3 constitute highly significant findings concerning the stability or reliability of lint yield. First, from a gravimetric point of view, it takes about 1.6 pounds of seed per acre to yield 1 pound of lint. If a variety depends heavily on the number of seed per acre to produce an acceptable lint yield, then, it must fix a great deal more carbon to achieve this result. On a weight basis, it must produce about 1.6 times more carbon per pound of lint per acre. Cottonseed contains about 20 percent triglyceride, or oil. It takes approximately 2.25 time as much energy to produce a pound of triglyceride as compared to a pound of cellulose (West and Todd, 1956). Thus, on an energy equivalency basis, the cotton plant must fix nearly twice as must carbon to produce a pound of seed as compared to a pound of lint.

Evidence that the shift in major yield component contribution to lint yield presented above can result in more variable, less reliable lint yields is strongly supported by a comparison of the descriptive yield statistics for U.S. upland cotton for the periods 1960-1979 and 1980-1998. These data show that mean and maximum yield levels were improved in the more recent time period. In contrast, the minimum yield produced in recent years is lower than the minimum yield produced in earlier years by approximately 17 pounds of lint per acre. More importantly, the variance in yields for the recent time period compared to the earlier time period increased nearly four-fold. Similarly, the standard deviation nearly doubled. Additionally, the skewness in yield distribution of the recent time period was negative whereas it was positive for the earlier time period. This latter finding indicates that there were more low yielding years in the recent time period than in the earlier time period. The percent coefficient of variance in yield for 1980-1998 was 4.32 percent higher than the 1960-1979 era. These data represent strong evidence that upland cotton yields have become much more variable and less reliable in years between 1980-1998, as compared to years between 1960-1979.

A question arose concerning the relationship of the two major yield components i.e., the number of seeds per acre and the weight of fiber per seeds, to genetic differences and location or environmental effects. Figure 4 shows how the weight of fiber per seed varied with two modern varieties, Acala Maxxa and Suregrow 125, across nine Beltwide locations from Florence, SC to Shafter, CA in 1996. These data demonstrate that Acala Maxxa always produced more weight of fiber per seed than Suregrow 125, regardless of location. Furthermore, the data clearly show that the weight of fiber per seed varies dramatically by location for both varieties. The level of variation, for both varieties is very similar in direction, attains a minimum value at the Dallas, TX location and approaches maximum levels at the eastern and western extremes of the U.S. cotton belt, suggesting little genotype x environment interaction. In addition, the difference in the weight of fiber per seed between the two varieties appears to remain relatively constant across locations. This finding indicates that the two varieties are genetically different for this trait, and it may be manipulated through breeding.

Figure 5 shows these same data with the locations represented by degrees of west longitude, which allows for meaningful mathematical analysis and the development of best fit equations for the variation in weight of fiber per seed by location and variety. Two quadratic equations were obtained with R^2 values of 0.65 and 0.56 for Acala Maxxa and Suregrow 125, respectively. Inspection of these curves reveals that the two varieties differ in the weight of fiber per seed by approximately 15 milligrams across locations. Calculation of the rate of change in the weight of fiber per seed for the two varieties across locations from the first derivatives of the two quadratic equations, resulted in rates of about 143 and 118 micrograms of fiber per seed per degree west longitude for Acala Maxxa and Suregrow 125, respectively. This represents a difference in rate across locations for the two varieties of approximately 25 micrograms of fiber per seed per degree west longitude.

Figure 6 shows the variation in the number of seeds per acre across nine Beltwide locations for Suregrow 125 and Acala Maxxa. In this case, Suregrow 125 produced more seeds per acre than Acala Maxxa, however, the direction of variation tends to be very similar for both varieties. Figure 7 illustrates these same data but with the degrees of west longitude substituted for the physical location. This presentation of the data allows for the development of best-fit equations and a more useful mathematical analysis of the data. A quartic equation was the best fit for both varieties. The equation for Suregrow 125 had an R^2 value of 0.73, whereas the equation for Acala Maxxa had an R^2 value of 0.71. Suregrow 125 produced the largest number of seeds per acre at all locations but the general shape of the curves was very similar for both varieties. Suregrow 125 displayed the highest level of variation in number of seeds per acre across locations, while Acala Maxxa tended to be less variable. Here, again, the number of seeds per acre appeared to be under some level of genetic control.

Subsequent mathematical analysis of the relationship of the weight of fiber per seed and the number of seeds per acre with the total lint yield per acre across the nine Beltwide locations, showed that Acala Maxxa produced approximately 70 micrograms of fiber per seed per pound of lint yield per acre. On the other hand, Suregrow 125 produced about 50 micrograms of fiber per seed per pound of lint yield per acre. Suregrow 125 produced about 4200 seeds per pound of lint yield per acre across the nine Beltwide locations, while Acala Maxxa produced approximately 2800 seeds per pound of lint yield per acre. These data constitute strong evidence that Acala Maxxa depends heavily on more fiber per seed and fewer seeds per acre to produce its lint yield, while Suregrow 125 relies heavily on its ability to produce more seeds per acre and less weight of fiber per seed to produce its lint yield.

Summary

Based on the above reported changes in yield component contribution to total lint yield in the 1980-1998 era as compared to the 1960-1979 era and the data discussed above concerning the gravimetrics and energetics of cellulose versus cottonseed oil biosynthesis, it seems apparent that what is needed are genetic types which can produce their yield from more weight of fiber per seed and fewer seeds per acre. The optimum combination of these two major yield components in a commercial variety should result in more lint yield at a lower energy cost to the plant and, thus, more reliable and stable yields. Acala Maxxa and Suregrow 125 appear to be two, undoubtedly among many reasonable parental choices for initial crosses to achieve this end. We suggest that the appropriate resources be directed towards development of such germplasm in the public sector followed by the free exchange of germplasm to support private sector variety development.

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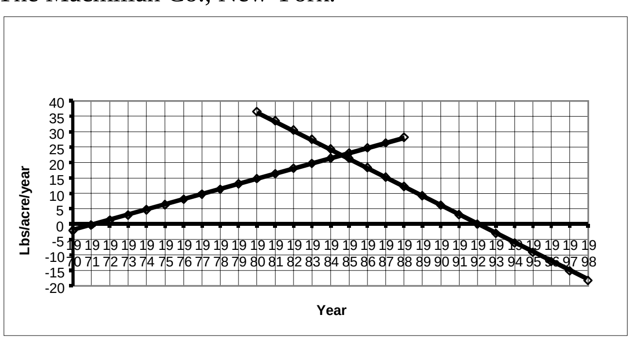

Figure 1. Mid-South Yield Trend: Overlapping Segmental Rate Analysis, 1970-1988 and 1980-1998.

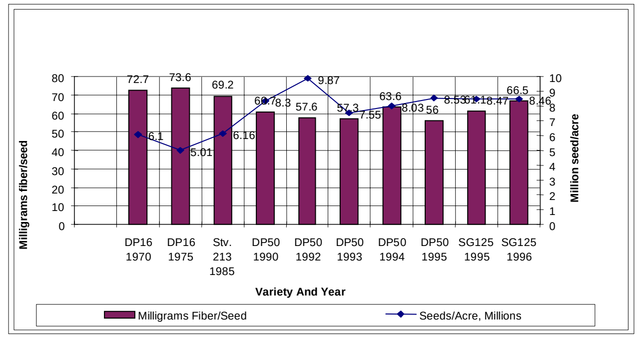

Figure 2. Mid South Region Yield Components: Milligrams Of Fiber Per Seed And Number Of Seeds Per Acre By Year And Variety, 1970-1996.

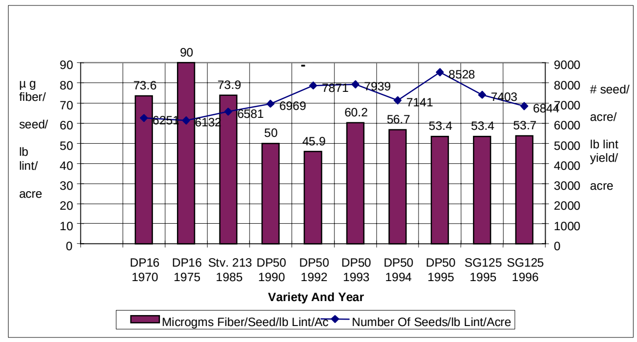

Figure 3. Mid-South Region Yield Components: Change In Yield Components Per Pound Of Lint Yield Per Acre By Year And Variety, 1970-1996.

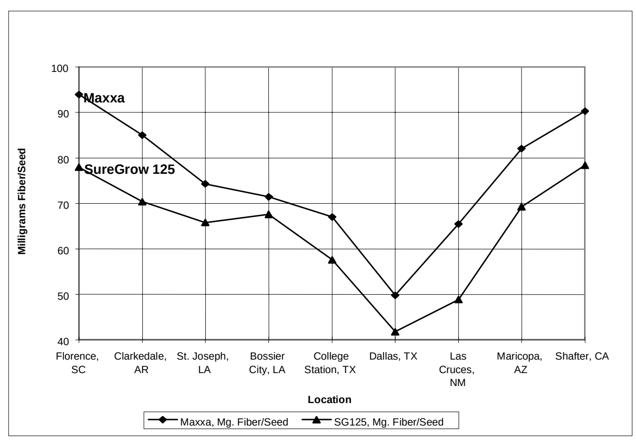

Figure 4. Acala Maxxa And SureGrow 125:Milligrams Of Fiber Per Seed By Variety And Location; 9 Beltwide Locations, National Variety Test, 1996.

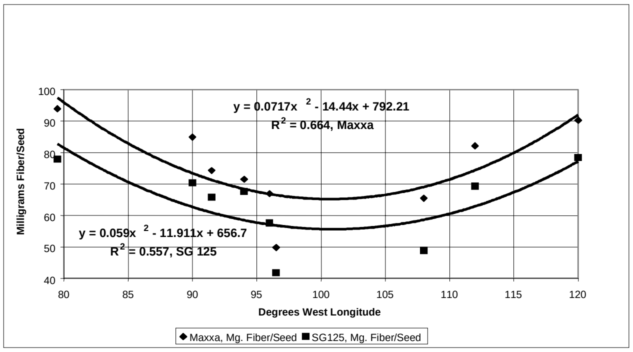

Figure 5. Acala Maxxa And SureGrow 125: Change In Milligrams Of Fiber Per Seed With Change In Degrees Of West Longitude, 9 Beltwide Locations, Regional Variety Test, 1996 (Best Fit Equation).

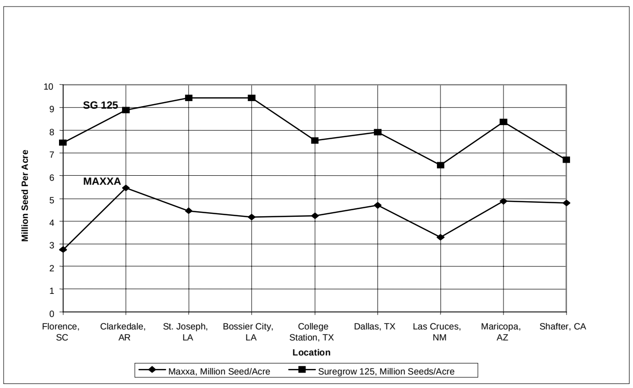

Figure 6. Acala Maxxa And SureGrow 125: Change In Millions Of Seed Per Acre With Change In Location; 9 Beltwide Locations, Regional Variety Test, 1996.

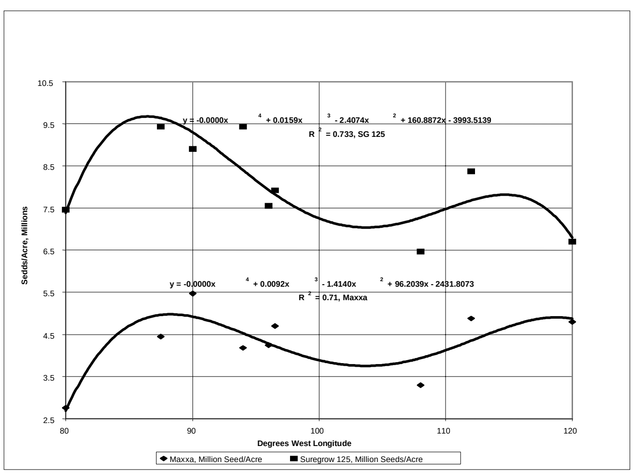

Figure 7. Acala Maxxa And SureGrow 125: Change In Millions Of Seeds Per Acre With Change In Degrees West Longitude; 9 Beltwide Locations, National Variety Test, 1996.