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BREEDING AND GENETICS

The Future of Cotton Breeding in the Western United States

Mauricio Ulloa*, Richard Percy, Robert B. Hutmacher, and Jinfa Zhang

ABSTRACT

Traditional breeding efforts dramatically transformed the cotton (*Gossypium* spp.) plant during the last century. In the coming decade, the high priority breeding objectives for production regions of the western US (far-western Texas, New Mexico, Arizona, and California) will involve morphologically complex traits controlled by many interacting genes. Although perennial concerns regarding yield, response to pests (lygus, thrips, aphids, and whitefly), and disease resistance (seedling fungal diseases, Fusarium and Verticillum wilts, and root-knot nematode) remain, plant characteristics conferring improved water-use efficiency, heat tolerance, and fiber quality traits will become increasingly important to the cotton industry. Adoption of transgenic cotton in New Mexico in the early 2000s resulted in decreased planting of conventional Acala 1517 cultivars, which declined to approximately 5% of total planting by 2005. However, a transgenic cultivar containing Bt, Acala 1517-99W, became available in 2006 and planting of that cultivar increased to 14% of total production in that same year. In Arizona, improvements in productivity and fiber quality in American Pima (*G. barbadense* L.) were made possible by emphasizing selection for adaptation to high temperature environments. However, yield losses attributed to heat stress continue to be significant in Upland, Pima, and Acala cottons, with long-term estimates averaging about 12% annually in Arizona alone. Further improvements will require the development of better selection tools, both phenotypic and molecular, for heat tolerance. In California, Fusarium wilt race 4 currently poses new challenges, making breeding for resistance against this pathogen a priority. With cotton hectarage declining in the western production regions from approximately 800,000 ha in the 1970s to less than 285,000 today, and a continuing shift in production from Acala to Pima, sustainability of the industry will likely require that breeders emphasize high yields, reduced production inputs, and lint characteristics that attract premium prices.

The history of cotton (*Gossypium* spp.) cultivar development traces to well before the advent of the science of plant breeding and genetics (Smith et al., 1999). Following the domestication of cotton, cultivation in discrete areas of Mesoamerica led to the development of the landraces recognized by the cotton scientists of the last century (Smith et al., 1999; Ulloa et al., 2007). During the last 70 years, traditional breeding has dramatically transformed the cotton plant. Today, cotton is the most important natural textile fiber and the world's sixth largest source of vegetable oil. The demand for cotton has been steadily growing, even though its share as a percent of total fiber production has declined substantially since the introduction of synthetics. In the early 2000s, consecutive annual records for cotton consumption were reported, with a net gain of 2.6 million tons of cotton finding its way to textile mills (Valderrama, 2004). However, profitability for cotton growers has been affected by recent fluctuations in price and price supports, fiber quality issues, and increases in production costs such as fertilizers, energy, and labor. Despite a historic trend toward increasing yields since 1922, yield plateaus and even short-term declines have been experienced in multiple production areas within the last 50 years (Culp and Green, 1992; Meredith, 2000).

Over the last 30 years, the cotton germplasm base used in plant breeding has narrowed. This relatively narrow genetic diversity, which has been suggested as a contributor to an apparent plateau in breeding progress, might also represent an impediment to efforts to sustain high yields (Lewis, 2001;

M. Ulloa, USDA-ARS, Western Integrated Cropping Systems Res. Unit, 17053 N Shafter Ave., Shafter, CA 93263; R. Percy, USDA-ARS, SPARC, Crop Germplasm Research Unit, 2881 F&B Road, College Station, TX 77845; R.B. Hutmacher, Department of Plant Sciences, University of California, Davis, One Shields Ave., Davis, CA 95616; J. Zhang, Department of Plant & Environmental Sciences, New Mexico State University, University Ave., Las Cruces, NM, 88003
*Corresponding author: mauricio.ulloa@ars.usda.gov

May et al., 1995; Meredith, 2000; Ulloa et al., 2006a; Zhang et al., 2005a). Growth and competitiveness of the cotton industry are dependent upon continuing improvements in yield, fiber quality, and pest resistance. There is strong pressure for the use of exotic germplasm sources in breeding, but large blocks of genes that are also introgressed during recombination between two parental lines (linkage drag) has limited the use of such germplasm. As cotton landraces disappear, the accessions that are preserved *ex situ* will be our only access to the genetic diversity that once resided *in situ* in Mesoamerica, South America, Africa, Arabia, and Asia (Ulloa et al., 2006a, 2007).

The field of genomics applies molecular tools and technology to the study of entire genomes, and has significantly impacted agriculture. This new DNA technology can be used as a tool to facilitate the breeding process through marker-assisted selection (Paterson and Smith, 1999; Ulloa et al., 2007). DNA markers are especially useful for targeting specific traits or genes of interest, monitoring alien genome introgression, providing a genetic basis for selecting particular regions of a genome that are targeted for introgression, thereby increasing the probability of choosing a desirable trait, and for reducing the size of breeding populations by evaluating the materials at early stages (Frelichowski et al., 2006; Park et al., 2005; Ulloa et al., 2007).

Because of declines in cotton production to less than 285,000 ha in New Mexico, Arizona, and California, and shifts from production of Acala to non-Acala Upland and Pima cultivars, concerns regarding yield, responses to pests, plant water-use efficiency, heat tolerance, fiber quality, and fiber uniformity will become increasingly important to the western cotton industry. Cotton growers will continue to demand high yields combined with more efficient per unit production, as well as lint characteristics that attract premium prices. Herein, we present an overview of the history, direction, and future of cotton breeding in the Western US.

A BRIEF HISTORY OF COTTON BREEDING IN THE WESTERN US

Two United States Department of Agriculture (USDA) scientists discovered the predecessor of today's Acala cotton (*Gossypium hirsutum* L.), in the small town of Acala, State of Chiapas, in southern Mexico during an expedition in 1906 searching for boll-weevil–resistant wild cottons (Smith et al., 1999; Ware, 1936). This cotton plant was described as a large, vigorous plant with large bolls and leaves, and seeds with high-quality fiber. This source of germplasm was the beginning of a rich and productive era of cotton breeding and production for the irrigated deserts of the southwestern US where the boll weevil problem was minimal or nonexistent (Shoemaker, 1911). Acala germplasm and commercial cultivars are known to produce high lint yields with excellent fiber quality when they are grown in New Mexico, Arizona, and California.

New Mexico has a rich history of cotton improvement, having one of the most influential breeding programs in the US in the last 80 years. This program has released approximately 30 Acala cultivars as well as other germplasm (Smith et al., 1999; Staten, 1970; Zhang et al., 2005b). Approximately 45% of cotton cultivars released in the US from 1950 to 1990 contained New Mexico germplasm in their pedigree (Bowman et al., 2006). The first Acala cultivar from the New Mexico Agriculture Experiment Station was College Acala, a reselection from the California Acala P12 cultivar released around 1928 (Stroman, 1948). Further improvement was achieved in 1951 with the release of Acala 1517C, which had large bolls suited for hand-picking as well as spindle-picker harvest and good fiber quality. Another significant improvement in New Mexico Acala was the incorporation of Verticillium (*Verticillium dahliae* Kleb) wilt resistance. Before the 1970s, Acala 1517 cultivars in New Mexico produced consistently low yields and received heavy discounts for low micronaire (below 3.5) from immature fibers under conditions of cool and shortened growing seasons. This problem was reduced in the late 1970s, with much of the improvement attributed to selections for earlier maturity (Smith et al., 1999). The preferred method of cultivar improvement within the Acala 1517 cotton types in the 1970s was single-plant selection (Cantrell et al., 2000; Davis et al., 1978a, 1978b). The development and release of Acala 1517-88 represented a gain in lint percentage (40.3%) compared to the 1517-77 cultivar (38.4 %) (Roberts et al., 1988). The genetic diversity present in Acala 1517 cotton types has proven to be a rich reservoir for yield potential and fiber quality within New Mexico cultivars and germplasm (Staten, 1970).

Extra-long staple cotton (*G. barbadense* L.) became established in the southwestern US in 1902. Egyptian cultivars were introduced, selected within, and intermated to produce American-Egyptian cultivars. In the late 1940s, a large heterogeneous gene pool was created from which the first Pima cultivar was developed (PS 1). In Arizona, these early breeding efforts emphasized adapting Egyptian and/or American Pima cultivars to the southwestern states. This involved the acquisition of heat tolerance or heat avoidance. Heat avoidance traits relate to height of first fruiting branch, plant height at season's end, and flowering rate (Feaster and Turcotte 1965; Feaster et al., 1980). However, these same traits were observed to be neutral or even disadvantageous in the absence of heat stress (Feaster and Turcotte, 1965).

More than 50 years of selection for productivity under high temperature conditions within Pima (also referred to as American Pima) germplasm has led to the inadvertent selection for increased stomatal conductance (Lu et al., 1998; Radin et al., 1994). Apparently, higher stomatal conductance levels have led to higher evaporative cooling rates and heat avoidance under irrigated conditions in the arid Southwest (Ulloa et al., 2000). With Pima production shifting away from low desert localities to the more moderate environment of California's San Joaquin Valley (SJV), Pima cultivar development has tended toward slightly later maturing, more indeterminate genotypes.

In recent years, there have been renewed efforts to improve heat tolerance in both standard Upland germplasm and in Acala cottons. Selective tools for identification and selection of individual plants from large populations are needed for breeders to effectively select for this trait. In the absence of such tools, measurements such as fruit retention rates, visual pollen sterility ratings, and yield potential in the presence of heat stress are being used with some success (Percy et al., 2006). The use of such measurements to evaluate heat tolerance is contingent upon a dependable heat stress environment. For this reason numerous public and commercial breeding efforts have established evaluation nurseries in the low desert environment of Arizona.

Although cotton was introduced and tested on a small scale at multiple sites in California in the mid- through late-1800s, the primary period of cotton production in California started with the introduction of Acala germplasm in the late 1910s. Over a 10-yr period, a reselection from a seed increase production field of Acala 8 imported from Texas produced the foundation seed for a commercial Acala cultivar in California. In 1925, the "one-variety law," which allowed the production of only Acala cotton in the SJV, passed, and California Acala cotton became synonymous with SJV cotton production (Smith et al., 1999). The one-variety law did not apply to other cotton production areas in California, such as the southern California low desert areas. USDA cotton breeders from the Shafter Research and Extension Center headed breeding efforts in California, with goals of improving yield, fiber quality, and disease resistance. Their first breakthrough cultivar was Acala 4-42, released in 1945 (Smith et al., 1999). From the early 1950s to the early 1960s, J. Turner (1981) used a Triple Hybrid-Early Fluff (THEF) as a parent to produce several lines that improved the SJV cotton. In the 1960s, a new and upcoming cultivar in the SJV was tested and released by the cotton testing committee. The new cultivar was adopted in the district and the prior cultivar typically was no longer maintained.

In the late 1960s, H. B. Cooper and J. Turner introduced New Mexico State University (NMSU) Acala germplasm lines that were crucial for the control of Verticillium wilt disease (Smith et al., 1999; Turner, 1981). In 1967, Acala SJ-1 was released with improved yield, early maturity, improved fiber quality, and slightly better Verticillium wilt resistance than Acala 4-42. SJ-1 originated from a cross of AxTE-1 and NM2302 (later released as 1517D). In 1973, SJ-2 was released, followed by SJ-3 in 1975, SJ-4 in 1976, and SJ-5 in 1977 (Smith et al., 1999; Turner, 1981). The one-variety law approach by the Acala Cotton Board continued into the 1960s and early 1970s.

Growers interested in a greater diversity of cotton cultivars also sought the help of University of California researchers. The interest in more cultivars eventually produced changes in California's one-variety law. In 1979 the law was successfully challenged, allowing private breeding companies to develop Acala cultivars for the SJV. USDA-ARS closed the cotton breeding program at Shafter in 1978, and all of the cotton germplasm from the USDA breeding program was transferred in 1983 to the producer-owned California Planting Cotton Seed Distributors (CPCSD), now owned by Bayer CropScience. The USDA germplasm was also released to private breeders who continued the breeding efforts for SJV cotton growers. After the USDA closed the breeding program in Shafter, growers in the SJV planted cultivars produced by CPCSD for nearly 20 years. In addition to CPCSD, companies such as Germains, Phytogen (Dow AgroSciences), and Delta and Pine Land Company (Monsanto) have gained market share in California during the last 25 years. With a broader range of cultivars available, the SJV became more of a High-Fiber Quality District instead of a One-Variety District.

What is now known as the San Joaquin Valley Cotton Board (SJVCB) was known as the Acala Cotton Board prior to the broad commercial introduction of Pima cotton into the SJV. The Acala Board established testing procedures for new cultivars to be grown in the SJV District. Initially, the Board established a cultivar to be designated as a standard for comparison based on yield performance, growth habit, and maturity suitability for SJV production. In addition, this standard cultivar needed to have minimum acceptable values for various fiber quality parameters. Cultivars entered in the testing program were grown and compared against the standard cultivar grown in the same locations in a 3-yr, multiple-site field testing program. Cultivars could be considered for approval by the Acala Cotton Board if they met or exceeded characteristics of the standard cultivar grown in the same test sites. Upon approval they became eligible to be grown in the SJV district. New standard cultivars have been selected over time as yield and quality improvements became available in newer cultivars. A separate but otherwise identical Pima cultivar testing program involving the selection of a Pima standard cultivar and a 3-yr testing program was set up in 1991. The current (2009) standards for Acala and Pima are Phytogen-72 (PVP 2001100115; Phytogen-Dow AgroScience Co.) and Phytogen-800 (US Patent 7332.657; Phytogen-Dow AgroScience Co.), respectively.

In the last five years, the availability of transgenic cultivars, particularly herbicide-resistant cultivars in Acala and non-Acala Uplands, have changed the criteria of some growers for cultivar choices. Transgenic cultivars are perceived as having economic impacts on production costs. As has happened in other cotton production regions, future development and availability of insect-resistant transgenic technologies that target insects of economic importance in California (such as aphid, lygus, some Lepidoptera) will likely continue to impact cultivar choices.

The timing of commercial availability of herbicide or insect-resistant transgenic Pima germplasm has been behind that experienced for Acala and non-Acala Uplands in California. During the 2008 growing season, there were more experimental cultivars and seed increase plantings of transgenic Pimas than Acala or Upland. SJV cotton cultivars are well known for their ability to achieve high lint yields and to produce superior fiber quality. These achievements have been possible because of the strong commitment of the California cotton growers to support and maintain a testing program to identify new cultivars that meet stringent standards for yield and fiber characteristics.

The USDA breeding effort that was discontinued in the late 1970s was reestablished in December of 2001. Today, the original mission of the USDA-ARS Genetics/Breeding efforts at Shafter CA, "to develop and distribute cotton germplasm particularly suited for San Joaquin Valley conditions" is being continued and maintained by the Western Integrated Cropping Systems Research Unit (WICSRU). Research emphasis now focuses on the development of new and improved germplasm, and the development and application of molecular markers to study structural genomics (genetic mapping) and determine genome linkage relationships for important traits. These markers are used to target candidate genes or quantitative trait loci for integrating into improved germplasm through marker-assisted selection. In only six years, with the collaboration of other public breeding programs and the University of California, old germplasm has been recaptured, and new ones have been developed. Recently, the first Upland germplasm line from the WICSRU breeding program (SJ-U86) was released (Ulloa et al., 2006c). The WICSRU also participated in the release of four additional Upland lines : AGC85, AGC208, and AGC375 (Percy et al., 2006) and CRB 252 (Percy et al., in press).

To speed the effort to increase the number of cotton cultivars resistant to Fusarium wilt (caused by *Fusarium oxysporum* f.sp. *vasinfectum* Atk. Sny & Hans) (FOV), the USDA-ARS, the University of California, and New Mexico State University jointly registered and released four Pima cotton germplasm lines [SJ-07P-FR01 (Reg. No. GP-910, PI 654065), SJ-07P-FR02 (Reg. No. GP-911, PI 654066), SJ-07P-FR03 (Reg. No. GP-912, PI 654067), and SJ-07P-FR04 (Reg. No. GP-913, PI 654068)]. Germplasm SJ-07P-FR01 – FR03 originated from a cross of germplasm lines 8810 and NMSI 1601. SJ-07P-FR04 is a population originating from reselection within P73. This is the first public release of Pima lines possessing good levels of resistance to FOV race 4. Based on the results of field and greenhouse studies, these lines possess good, but not complete, levels of resistance to FOV race 4. In addition, these lines produced moderate yields of cotton lint with good to superior fiber length and strength (Ulloa et al., 2009). Cotton breeders in California need alternative sources of germplasm for improving resistance of Pima cottons to this disease. SJ-07P-FR germplasm lines will provide needed alternative sources of FOV resistance and will broaden the genetic base of resistant germplasm critical to maintaining a healthy Pima cotton industry in the SJV of California.

HISTORY OF PRODUCTION LEVELS AND ASSOCIATED PROBLEMS

New Mexico. In the early 1900s, the Pecos and Mesilla valleys were the early sites of cotton production in New Mexico, but it was not until 1922 that cotton became a major crop in the state. Since a production peak in the 1950s, combined hectarage of Acala and Upland cottons in New Mexico have declined from more than 121,000 ha in 1953 to approximately 16,000 ha in 2007. The production of Pima cotton has fluctuated over the years, averaging approximately 7,000 ha during the period of 1950 to 1972. In 2007, USDA reported only 3,600 ha of Pima planted in New Mexico (National Agricultural Statistics Service, 2007). Average lint yields of combined Acala and Upland cottons have increased from 651 kg ha^{-1} in 1972 to a high of 1,140 kg ha^{-1} in 2005. Lint yields for Pima cotton also increased from 391 kg ha^{-1} in 1972 to a high of 1,180 kg ha^{-1} in 2003 (Fig. 1).

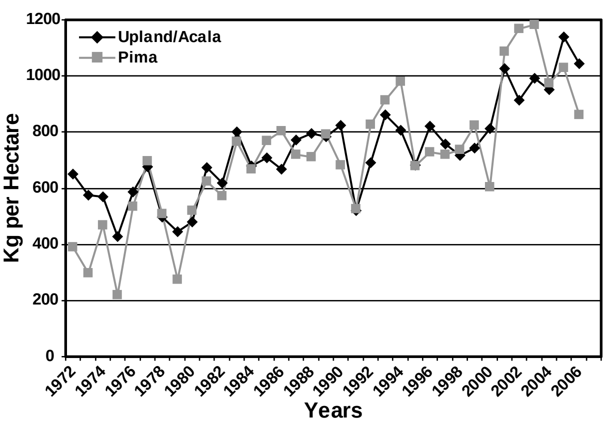

Figure 1. Yield per hectare for combined Acala and non-Acala Upland cottons and for Pima cotton from 1972 to 2006 in New Mexico.

Due to a shift in production from conventional to transgenic cotton in the late 1990s, and the unavailability of transgenic Acala cultivars in New Mexico, the hectarage of conventional Acala 1517 cotton declined to approximately 5% by 2005. However, Upland transgenic cotton did not match the Acala fiber quality. With the release of the first Bt Acala 1517 cultivar, 1517-99W, in 2005, New Mexico growers again had the option to plant an Acala cultivar. The 1517-99W cultivar gained 14% of planted hectares the following year and 7% cotton acreage in 2007. However, its seed production was terminated in 2008 due to its limited adaptation.

The decline in New Mexico cotton hectarage has resulted from high production costs, low prices for raw cotton, and competition from urbanization of cultivated land and other crops offering higher net value, such as pecans, alfalfa, and silage crops. In addition, root-knot nematodes [*Meloidogyne incognita* Kofoid and White (Chitwood)] and Verticillium wilt diseases continue to cause approximately 5% yield loss annually.

Arizona. Although Arizona averaged about 147,000 ha of Upland cotton from the 1950s to late 1980s, hectarage has fluctuated with peaks as high as 243,000 in 1953 and 1981. For Pima cotton, the highest production occurred in 1989, with 99,000 ha. Combined hectarage of Upland and Pima cotton in Arizona steadily declined between 1990 (192,000 ha) to 2006 (78,000 ha) despite generally increasing yields. Some of the yield increase may be attributed to a shift in production from Pima cottons (decreasing from 43,000 ha in 1991 to 2,500 ha in 2007) to Upland cottons that are higher yielding in this high-temperature environment (National Agricultural Statistics Service, 2007). Additional factors contributing to this decline include increasing production costs, reduced lint prices, competition from alternate crops, and a loss of 33,000 ha of crop land in central Arizona to urban development. To further complicate matters, the loss of Pima hectarage has been accompanied by a loss of the specialized ginning facilities necessary to support Pima production.

Yield losses due to pink bollworm [*Pectinophora gossypiella* (Saunders)] and fiber quality problems due to whitefly [*Bemisia tabaci* (Gennadius)] were significant problems in Arizona before the adoption of transgenic cotton (Bt cotton). However, the adoption of Upland Bt cotton cultivars and the use of effective chemistry (primarily insect growth regulators) has suppressed these pests to less damaging levels. No transgenic Bt cultivars are available in the Pima cottons, and pink bollworm continues to be a problem in the extra-long staple cottons. Arizona currently has an active pink bollworm eradication program. With the effective control of whitefly and pink bollworm, the western tarnished plant bug [*Lygus hesperus* (Knight)] has emerged as a primary pest species. Management of lygus in Arizona cotton has proven difficult, often requiring treatment with broad spectrum insecticides. Presently, it appears that lygus will remain a perennial primary pest species.

California. As in the other western states, cotton hectarage in California has also fluctuated during the last 85 years. Metric ton production increased from 90,720 in the 1920s to more than 816, 470 tons yr^{-1} in the 1980s. The first white gold boom for California was observed around the 1950s with almost 405,000 ha in cotton production. This era of cotton in California (1951 to1965) was called the Vibrant Young Adult by Turner (1981). The era of the Mature King (Turner, 1981) in the late 1970s to early 1980s corresponded with annual production peaks of approximately 668,000 ha and 794,000 tons. The past two decades have seen a steady decline of Acala hectarage from approximately 445,000 ha in the late 1980s to an estimated 115,000 ha in 2007 (California Cotton Ginners and Growers Associations, 2007; CCGGA). Conversely, Pima hectarage has increased from approximately 40,000 ha in the late 1990s to more than 109,000 ha in 2006. Although total hectares planted to cotton has declined in California during recent years, lint yields for Acala and Upland cultivars have increased from 708 kg ha^{-1} in 1953 to a high of 1,730 kg ha^{-1} in 2004. Pima yields also increased from 276 kg to up to 1,117 kg during the same time (Fig. 2) (National Agricultural Statistics Service, 2007). In 2007, for the first time, estimated Pima cotton hectarage in California (121,000 ha) exceeded that of Acala and Upland cotton (81,000 ha) (CCGGA, 2007). This trend continued in 2009 with approximately 28,700 ha of Acala and 48,500 ha of Pima cottons (CCGGA, 2009). Currently, water shortages, increasing production costs, low prices for raw fiber, and competition for labor and other crops are making profitable cotton production a more difficult venture.

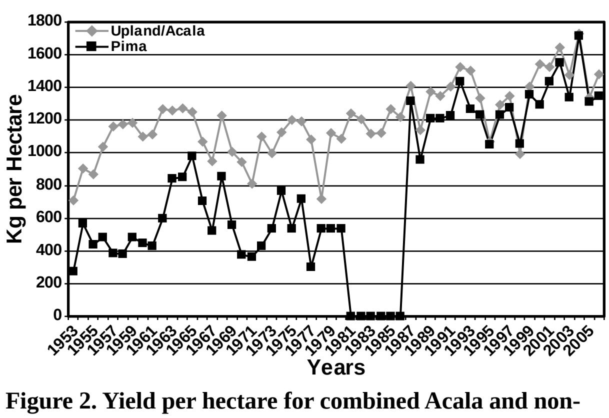

Figure 2. Yield per hectare for combined Acala and non-Acala Upland cottons and for Pima cotton from 1953 to 2005 in California.

Three major disease problems that have exerted severe pressure on California cotton production at different times are Verticillium wilt, FOV (Garber et al., 1979), and root-knot nematodes (Veech, 1984). Verticillium wilt was first identified in the SJV in 1927 (Herbert and Hubbard, 1932) and continues to be a recurring problem in California. Some races of Fusarium and root-knot nematode occur simultaneously in fields, and together act with devastating effect on the cotton crop. Before 2003, FOV in California was thought to be primarily caused by FOV race 1. This race is found typically in sandy soils and produces the most severe yield impacts when present in combination with root-knot nematodes (Bell, 1984; Veech, 1984).

Recently, University of California at Davis (UCD) scientists (Kim et al., 2005) identified a race 4 isolate of FOV in California soils. This race, first identified in India on Asiatic cottons, had not been identified previously as a problem in the US. Recent field investigations (Kim et al., 2005; Ulloa et al., 2006b) have found race 4 FOV in clay loam and loam soils, in which root-knot nematode populations and root damage symptoms were largely absent. Disease symptoms of the race 4 FOV isolate have been most severe in Pima cultivars. This pathogen also commonly infects Acala and Upland cottons. The current genetic base for FOV resistance for commercial Pima cultivars in California is limited (Hutmacher et al., 2005; Ulloa et al., 2006b). This disease could exert a significant impact on cotton production because the causal fungus has resting stages with greater longevity. In addition, a new virulent isolate of FOV has been identified recently in Australian cotton fields (Kochman et al., 2002; Wang et al., 2004). To date, the Australian isolate(s) of FOV has not been identified in the US. The vulnerability to pathogens such as the Australian and race 4 FOV of California, as well as other US production regions highlights the need for additional comprehensive research to protect the US cotton industry from introduced diseases or virulent strains that arise from within our borders.

Emphasis on improved fiber quality has long been a goal and direction of private and public breeding efforts for Acala cotton grown in California. This same philosophy from the SJVCB and the University of California cultivar testing efforts have been applied to Pima cultivars introduced in California since the early 1990s. In the past, a record of continuing improvements in some components of fiber or yarn quality have yielded price dividends, particularly with Acala cultivars from California. For a range of reasons, probably including improvements in average fiber quality from some other US production regions in recent years and other changes in mill customer demands, the size and consistency of price differentials paid for further advancements in fiber and yarn quality has been reduced. Hectarage reductions in Acala plantings and shifts out of Acala to Pima plantings in California in large part reflect the reduced incentives growers feel to grow Acala cottons unless market prices pay acceptable premiums or improved yields make them more competitive and profitable.

DIRECTIONS/STRATEGIES IN COTTON BREEDING

Increasing productivity and reducing production costs are significant goals to growers. It is also true that fiber quality has a large impact on overall profitability. Relatively stagnant or even declining cotton prices in recent decades have played an important role in highlighting that growers need higher production, and/or reduced input costs, to generate acceptable profits. Changes in yarn manufacturing technologies are driving how fiber quality is defined. The introduction of air-jet spinning means that fiber length, uniformity, and strength continue to be important, and thus, should continue to attract premium prices at the gin. Research programs today require measurements of agronomic and fiber quality traits such as lint percentage, boll weight, 2.5 and 50% fiber span length, fiber bundle strength, and fineness (e.g., micronaire reading, fiber maturity, fiber perimeter) to breed for the fiber properties that the textile industry requires for a new generation of textile technologies (Meredith, 2000; Smith et al., 1999; Ulloa, 2006).

Maintaining and improving fiber qualities of the Acala 1517 cultivars are important tasks for the NMSU cotton genetic/breeding program at Las Cruces, NM. This effort is facilitated by support and collaboration from the USDA-ARS Southwest Cotton Ginning Laboratory. The fiber qualities of Acala 1517 cultivars or germplasm are part of an important niche market (Zhang et al., 2005b). Continued introduction of insect and herbicide resistant transgenic Acala 1517 cultivars promises to reduce pest damage, increase yields, and maintain fiber quality characteristics (Zhang et al., 2008a). Recently, evaluation and breeding for Verticillium wilt and root-knot nematode resistance and tolerance for drought and salt stresses have also become an integral part of the breeding effort (Bajaj et al., 2008; Zhang et al., 2006, 2008b). In addition, extensive effort has been made to introduce desirable genes and traits from *G. barbadense* into Upland cotton (Zhang and Percy, 2007). At NMSU, efforts to support the breeding program with molecular technology started in the early 1990s. Research in genetic mapping of selected populations and marker-assisted selection is being conducted and developed to provide breeders with tools to speed the breeding process (Liu et al., 2000; Niu et al., 2007; Tatineni et al., 1996; Ulloa et al., 2000; Zhang et al., 2005a).

Development of heat tolerance in both Upland and Pima cotton will remain a primary goal of breeding in Arizona and reducing micronaire also will continue to receive attention in breeding efforts. Drought tolerance or water-use efficiency may become a more prominent breeding goal as water availability and conservation become serious issues in the Southwest. Recognizing that input costs are likely to continue to rise, strategies for increasing the value of the cotton crop in Arizona through increased fiber value or seed value are being investigated.

Water-use efficiency and drought tolerance also are becoming increasingly critical priorities in California. To remain competitive with alternative crops important to the dairy industry or horticultural markets, agronomic crops such as cotton will have to be produced with reduced input costs while maintaining adequate yields and quality. The possibility exists that an early-maturing or shorter-season cultivar could offer reduced inputs and production costs, however, this trait must come without major sacrifices in yield or fiber quality. Particularly with the mix of crops that can be grown under irrigation in the western US, potential for profitability will be impacted not only by commodity prices but by also by costs and availability of irrigation water and other sometimes limiting inputs. In California, there is considerable social pressure to make cotton production practices more compatible with those of other crops, and more environmentally benign to urban or suburban populations through use of reduced-risk pesticides. Recently, some counties in California have prohibited the planting of transgenic crops such as cotton. Although some of these counties have never produced cotton, their efforts have drawn attention that could lead to similar statewide ordinances.

Developing and growing resistant cultivars through breeding for host plant resistance can minimize chemical inputs and protect the environment. Plant biotechnology will continue to offer solutions by minimizing the damage from insects and weed pests through transgenic cultivars. In addition, continuing progress made in genomics research such as developing molecular markers, genetic mapping, and gene expression, should pay dividends to growers and the industry. This cutting-edge research area involves the study of all the genes expressed in a given organism and their collective effects on morphological traits. DNA markers tightly linked to the traits or genes of interest, and high throughput marker screening systems have had a significant impact on cotton improvement in recent years. A recent positive step was the establishment of an *ad hoc* bioinformatics resource, the Cotton Microsatellite Database at http://www.cottonmarker.org (sponsored by Cotton Incorporated). Currently, considerable attention is focused on the development of single nucleotide polymorphism marker systems, as they allow breeders to access sequence differences directly. In modern breeding programs, marker-assisted breeding, marker-assisted introgression, and marker-assisted selection will be a reality that will help breeders to speed the selection and development process of new cultivars.

A good example is the recent discovery of a molecular marker linked to root-knot nematode resistance (Wang et al., 2006). After the report of Wang et al. (2006), several research groups followed by developing new markers closely linked to SSR CIR316. Additional reports (Niu et al. 2007; Shen et al. 2006; Wang and Roberts 2006; Ynturi et al. 2006), which used different marker sources and cotton mapping populations, confirmed the importance of a specific region in chromosome 11 for vascular disease resistance.

To improve cultivar performance above current yield and fiber quality baselines, it is essential that new genetic variability be introduced into elite germplasm pools used by breeding programs. However, the complexity of the polyploid cotton genome will continue to complicate marker discovery and application. Continued development and improvement of high throughput marker systems will be a necessity as breeding programs need markers that can be easily and quickly applied. This DNA marker technology eventually will be incorporated into the breeding programs, speeding the efforts of cultivar development by marker-assisted breeding, marker-assisted introgression, and marker-assisted selection (Ulloa et al., 2007). In addition, recombinant DNA technologies (e.g., gene transformation/transgenic cotton) will benefit from such as advances by speeding transgene introgression or conversion of transgenic cultivars. The current status of cotton breeding in the western US is stable and strong. However, the need exists for maintaining and increasing support for public breeding programs to preserve the genetic diversity of the western cotton crop.

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DISCLAIMER

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA or the University of California.

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