Cotton

Joshua A. Lee

Cotton plants produce spinnable fibers, which are referred to as lint. These fibers originate as cells growing outward from the epidermis of the fertilized ovule. As the ovule enlarges, the cells elongate, and the cell walls are thickened as the protoplasts deposit successive layers of cellulose in a helical pattern. As the ovule matures into a seed, the protoplasts die, the cell walls collapse, and the cells become convoluted bands. The flattening and convolution of the cells provide the baffles that promote adhesion when the fibers are spun into yarn.

There are four domesticated species of cotton. *Gossypium arboreum* L. and *G. herbaceum* L., both diploids (2n = 26), are native to the Old World and are grown mostly in India where the lint is used for the production of textiles and for stuffing. *Gossypium barbadense* L. and *G. hirsutum* L., both allotetraploids (2n = 52), evolved in the New World. *Gossypium barbadense*, commonly known as extra-long-stapled cotton, supplies about 8% of the current world production of cotton fiber. Extra-long fiber is used mostly in the production of sewing thread and luxury fabrics. *Gossypium hirsutum*, known most widely as upland cotton, contributes about 90% of the current world production of cotton fiber. Upland fiber is used in many textiles products and various nonwoven products, such as cordage and stuffing. Linters, the short fibers removed from the seeds of upland cotton, are an important source of industrial cellulose. Although cotton is grown mostly for fiber, the seeds are an important by-product. Refined cottonseed oil is used for culinary purposes, and the cake from the extraction of oil is a valuable fertilizer and source of protein for ruminant livestock.

Cotton is grown virtually around the world in tropical and subtropical
latitudes, to 43° N latitude in the USSR, and to 45° N in the People's Republic of China. Open bolls and fiber of *G. barbadense* and *G. hirsutum* are illustrated in Figs. 5-1 and 5-2.

**TYPES OF CULTIVARS**

**Mode of Propagation**

All species of *Gossypium* propagate only from seeds. In the native habitat, the growth habit of most species of *Gossypium* is that of a perennial shrub or small tree. Species of *Gossypium* commonly are found growing in dry stream beds, and at the interfaces between stream banks, or beaches, and semiarid woodland (Fryxell, 1979). The wild races of the cultivated species are photosensitive in flowering response and bear fruit only at the onset of the dry season (Mauney and Phillips, 1963).

**Figure 5-1** Opened capsules (bolls) of cultivated cottons. *(Upper left)* *G. hirsutum* cv. 'Empire,' loose lock; *(lower left)* *G. hirsutum* cv. 'Paymaster 464,' stormproof type; *(upper right)* *G. barbadense* cv. 'Pima S-5;' *(lower right)* *G. barbadense* cv. 'Seabrook Sea Island.'
Modern domesticated cottons have been selected for fruiting under long days, during periods when soil moisture is ample, and at a lower node along the main plant axis than in the wild ancestors. Thus, there was a transition from perennial cropping, as in wild cottons and some tropical cultivars, to the annual habit of cottons grown in extratropical latitudes. Modern cotton cultivars, thus, differ in many important respects from their wild ancestors (Table 5-1).

In the United States, cotton is planted after soil temperature rises to 18°C. The seeds germinate in about 7 days. At daily maximum ambient temperatures of 26° to 28°C, modern upland cultivars begin to differentiate flower buds at the fifth to the seventh node, and these are ready for pollination in 21 to 24 days, the first usually about 60 days after seedling emergence. Ideal temperature regimes for the maturation of fruit in both *G. barbadense* and *G. hirsutum* are daily maxima around 32°C and nightly minima around 18°C (Brown and Ware, 1958).

Flowers are produced on lateral fruiting branches called sympodia. The sympodia up the main plant axis initiate flowering at intervals of 2 to...
3 days, and additional flowers are produced along a symposium at 6- to 7-day intervals. A cutaway view of a flower of *G. hirsutum* is illustrated in Fig. 5-3.

The corolla of a typical species of *Gossypium* consists of five petals united at the bases and continuous with the androecium (anther column) which clasps the ovary and the style. The androecium bears up to 100 anthers on filaments of varying length. The tip of the stigma is exerted above the androecium and displays from three to five sections, each continuous with a locule of the ovary. The ovules are borne at the central axis of the ovary and can number as many as 10 per locale in *G. hirsutum*, but usually fewer in *G. barbadense*.

After fertilization, the ovary develops into a valvate capsule called a

<table>
<thead>
<tr>
<th>Trait</th>
<th>Wild</th>
<th>Domesticated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>Semiarid tropics and subtropics; beaches and river banks</td>
<td>Tropical to temperate; cultivated fields; wide-spread as a crop</td>
</tr>
<tr>
<td>Germination response</td>
<td>Seeds impervious; germination sporadic</td>
<td>Seeds imbibe freely and germinate rapidly</td>
</tr>
<tr>
<td>Phenology</td>
<td>Sharply seasonal pattern of vegetative development followed by fruit production and dormancy</td>
<td>Short vegetative phase followed by overlap in vegetative and fruit development; plants usually destroyed after harvest</td>
</tr>
<tr>
<td>Fruiting</td>
<td>Perennial fruiting; 15 or more nodes along the main plant axis to the first fruiting branch</td>
<td>Annual fruiting; 5 to 7 nodes along the main plant axis to the first fruiting branch</td>
</tr>
<tr>
<td>Fruiting response</td>
<td>Requires short days, cool nights, and drought stress for orderly flowering and fruiting</td>
<td>Not short-day sensitive in fruiting response; prefers cool nights and ample soil moisture for best production</td>
</tr>
<tr>
<td>Fruit size and weight</td>
<td>Small; 2 g lint and seed</td>
<td>Larger; 5 to 8 g of lint and seed</td>
</tr>
<tr>
<td>Lint percentage</td>
<td>Low; 15 to 20%</td>
<td>Higher; 35 to 40%</td>
</tr>
<tr>
<td>Fiber</td>
<td>Lint short, fine, dingy brown in color</td>
<td>Lint variable in length up to 30 mm; coarse or fine; stronger and most often white</td>
</tr>
</tbody>
</table>
Figure 5-3  Cotton flowers. (Right) Cutaway view of a mature cotton flower showing the androecium and stigma; (center) a flower sealed for self-pollination with a paper clip; (left) an emasculated flower with a length of soda straw over the stigma and style.

boll. The maturation process requires from 40 to 80 days depending upon cultivar, ambient temperature, and placement on the plant. The capsule can be round, top-shaped, or ovate, and bears from 3 to 10 g of seed and lint.

Natural cross-pollination in cottons varies from none to as much as 60%, depending on the region, the size of the plot sampled, and the availability of pollen vectors (Brown and Ware, 1958). If no foreign pollen is available, both wild and domesticated species of Gossypium self-pollinate without any apparent loss of vigor.

Past and Present Cultivar Types

Herein, only cultivars of G. barbadense and G. hirsutum will be discussed. The Old World diploid cottons have evolved into numerous races and cultivars, but these are of only local importance today (Hutchinson et al., 1947). Evidence for the domestication of G. barbadense was found
among archaeological contexts in the Ancon-Chillon district of Peru dating from about 2200 to 1750 B.C. (Stephens and Moseley, 1974). The oldest known remains of *G. hirsutum* date from the Abejas phase of the Tehuacan Valley of Mexico, about 3500 to 2300 B.C. (Smith and Stephens, 1971). These seemed to have been remains of domesticated stocks, probably introduced from a center of diversity along the border of what is now Guatemala, the region from which the progenitors of modern upland cotton cultivars were derived (Hutchinson et al., 1947).

Modern upland cultivars of *G. hirsutum* stem from natural crosses among 'Georgia Green Seed,' 'Creole Black Seed,' and 'Burling's Mexican,' which were introduced from Mexico into the United States in the eighteenth and nineteenth centuries (Moore, 1956; Ramey, 1966). There is evidence that 'Sea Island,' a form of *G. barbadense*, contributed germplasm to modern upland cottons.

The first documented attempts to breed cotton occurred in Mississippi as early as 1830 and involved mass selection of productive plants with improved lint (Moore, 1956). The approximate pedigree of a modern upland cultivar stemming from 'Petit Gulf,' an early selection, is illustrated in Fig. 5-4.

Late in the nineteenth century, the number of cotton cultivars offered to American growers numbered in the hundreds. These were very variable, both within and among cultivars, for plant habit, lint yield, and fiber properties. Efforts were made to classify upland cultivars by type in the

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**Figure 5-4** Approximate pedigree of the modern *G. hirsutum* cv. 'Carolina Queen.'

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Burling's Mexican  --- Georgia Green Seed
                        |  Creole  Sea Island
                        |          |       (1833)
                        |  Petit Gulf
                        |      |  Cleveland
                        |      |                  
                        |      |  Stoneville 2
                        |      |                  
                        |      |  Wannamaker
                        |      |      Cleveland
                        |      |                  
                        |      |  Cleveland 884
                        |      |      Clevewilt
                        |      |                  
                        |      |  Coker 100
                        |      |                  
                        |      |  Coker 100W  Empire WR
                        |      |                  
                        |      |  Carolina Queen  (1965)
```
hope of standardizing materials for production and breeding purposes (Brown and Ware, 1958). According to Brown and Ware, J. H. Mell of Alabama offered the first such classification in 1891, arranging upland cultivars into seven types based on various morphological features. In 1925, H. D. Brown classed upland cultivars into seven types based mostly on boll size and fiber length. In 1958, Brown and Ware recognized 16 upland types based on boll size, plant form, fiber properties, and region where grown (Table 5-2).

Early attempts at typifying cotton cultivars were somewhat artificial

<table>
<thead>
<tr>
<th>Type</th>
<th>habit</th>
<th>Boll size</th>
<th>Fiber length</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Deltapine'</td>
<td>Medium tall, spreading</td>
<td>Medium</td>
<td>27–29 mm</td>
</tr>
<tr>
<td>'Stoneville'</td>
<td>Medium tall, spreading</td>
<td>Large</td>
<td>26–27</td>
</tr>
<tr>
<td>'Delfos'</td>
<td>Medium tall, spreading</td>
<td>Medium</td>
<td>28–30</td>
</tr>
<tr>
<td>'Coker 100'</td>
<td>Medium tall, upright</td>
<td>Medium</td>
<td>26–28</td>
</tr>
<tr>
<td>'Fox'</td>
<td>Short, spreading</td>
<td>Small</td>
<td>26–28</td>
</tr>
<tr>
<td>'Empire'</td>
<td>Short, compact</td>
<td>Large</td>
<td>26–28</td>
</tr>
<tr>
<td>'Rowden'</td>
<td>Medium tall, spreading</td>
<td>Large</td>
<td>24–26</td>
</tr>
<tr>
<td>'Mebane'</td>
<td>Short, compact</td>
<td>Large</td>
<td>24–26</td>
</tr>
<tr>
<td>'Triumph'</td>
<td>Short, compact</td>
<td>Medium</td>
<td>25–26</td>
</tr>
<tr>
<td>'Western'</td>
<td>Short, compact</td>
<td>Medium</td>
<td>25–26</td>
</tr>
<tr>
<td>'Mebane'</td>
<td>Short, compact</td>
<td>Large</td>
<td>22–25</td>
</tr>
<tr>
<td>'Hibred'</td>
<td>Short, compact</td>
<td>Large</td>
<td>24–26</td>
</tr>
<tr>
<td>'Lankart'</td>
<td>Short, compact</td>
<td>Large</td>
<td>24–26</td>
</tr>
<tr>
<td>'Paymaster'</td>
<td>Short, compact</td>
<td>Large</td>
<td>25–26</td>
</tr>
<tr>
<td>'Acala'</td>
<td>Tall, spreading</td>
<td>Large</td>
<td>28–30</td>
</tr>
<tr>
<td>'Long Staple'</td>
<td>Various</td>
<td>Mostly large</td>
<td>32–38</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Various</td>
<td>Various</td>
<td>22–28</td>
</tr>
</tbody>
</table>
and did not always relate to utility. Niles and Feaster (1984) emphasized that current views of cultivar type are better guides to breeding and utilization. In areas where stripper harvest is used, early cultivars with a compact fruiting zone and storm-resistant bolls (Fig. 5-1) are preferred. In regions where spindle pickers are used, taller and later cultivars with moderately long limbs and loose-locked bolls (Fig. 5-1) are required. In the arid West, full-season cultivars, such as ‘Pima’ (G. barbadense) and ‘Acala’ (G. hirsutum), are grown for the production of high quality lint.

The first annual G. barbadense cultivars were the Sea Island stocks brought to Georgia and South Carolina from the West Indies between 1767 and 1786 (Stephens, 1976). Although Sea Island cottons diverged into many locally grown strains, cultivars types were not classified until near the end of the nineteenth century. The production of the fine, very long, and strong lint of Sea Island cultivars thrived in the coastal belt of South Carolina and Georgia until destroyed by the boll weevil (Anthonomus grandis Boh.) in 1918. Sea Island cottons have contributed to the breeding of other types of G. barbadense and to the improvement of upland cultivars.

Egyptian cultivars of G. barbadense date to Jumel’s tree cotton, a perennial Peruvian stock introduced into Egypt around 1820. Jumel’s cotton hybridized with Sea Island stocks, and the result was the distinctive annual Egyptian cultivars grown today (Brown and Ware, 1958).

The first Pima cultivars were direct selections from Egyptian cottons. Modern Pima cottons are a small group of productive cultivars of interspecific origin (Bryan, 1955; Feaster and Turcotte, 1962). Egyptian and Pima cottons yield fiber that is longer, stronger, and finer than most upland cultivars, and both the Pima and Egyptian cultivars are adapted for production under irrigation in arid regions.

The Tanguis cultivars of Peru produce strong, long, and coarse lint that is used for the manufacture of high-quality denim cloth. According to Brown and Ware (1958), the Tanguis cottons were derived from a native perennial cultivar of G. barbadense, ‘Semi-Aspero,’ in 1908. Tanguis is grown as a ratooned crop (production after annual pruning for a number of seasons), and represents about 90% of the Peruvian crop. Tanguis cottons are grown commercially only in Peru, but have been used in the improvement of Pima cultivars.

EXTENT AND NATURE OF BREEDING PROGRAMS IN NORTH AMERICA

Although cotton is an important crop in Mexico and Central America, these regions grow mostly introductions. Cotton breeding in North America is centered in the United States, where there is both public and
private effort. The largest public breeding facility is located at Texas A&M University which supplies upland cultivars for about 34% of the more than 2 million ha of cotton grown yearly in Texas. The breeding of Pima cotton is centered at Phoenix, Arizona, and is funded by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS). There are public breeding programs in Missouri, Georgia, South Carolina, New Mexico, Mississippi, and Louisiana.

More than 60% of the more than 6 million ha of cotton grown yearly in the United States are planted to cultivars bred by private companies. These firms are located from California to the Atlantic Coast and supply cultivars for all of the cotton adaptational zones recognized by Abou-El-Fittouh et al., (1969). These are the western zone, which encompasses the arid West, the High Plains zone of north Texas and Oklahoma, the Delta zone centered in the alluvial valleys of the Mississippi basin, and the eastern zone which extends from the Mississippi Valley to the East Coast, north of the Delta zone in Tennessee and Missouri, and downward through eastern Texas. Besides breeding cultivars for the various adaptational zones in the United States, private firms supply upland cultivars for production in Latin America, some of the Mediterranean countries, and Australia.

Private firms in the United States breed only upland cultivars. However, a broad selection of these—more than 20 in 1985—are offered. Yet, less than 12 cultivars were grown on more than 55% of the total area planted to cotton in the United States in 1985. Private cultivar development in the United States has increased since the enactment of the Plant Variety Protection Act in 1970.

**BREEDING OBJECTIVES FOR CULTIVAR DEVELOPMENT**

There are no perfect cotton cultivars. All have weaknesses, some obvious at the time of release, and others becoming apparent after a few seasons of culture. Frequently, negative genotypic correlations among various economic traits create problems for cotton breeders such that the end product represents a compromise among the traits available for selection. Combining all the desired traits, including fiber yield, fiber quality, harvestability, and resistance to insects and pathogens, into a single cultivar, seems virtually impossible. The tenure of use of a successful cotton cultivar is 10 years or less (Niles and Feaster, 1984).

**Agronomic Traits**

Fiber yield has always been the primary objective of the cotton breeder because the greatest profit to the grower usually is realized from maximiz-
ing yield. The components of fiber yield were identified by Worley et al. (1976) as weight of fiber per seed, number of seeds per boll, and number of bolls per unit area. Lint percentage, the fraction of the unopened cotton that is fiber, is not a true component of yield, but is usually treated as such by cotton breeders. Growers prefer cultivars with high lint percentage because the costs of producing and processing fiber for market are less with such cottons.

Genotypic correlations between lint percentage and fiber yield in upland cotton ranged from 0.70 to 0.90 in various studies summarized by Meredith (1984). Meredith also reported heritability estimates for fiber yield ranging from 0.29 to 0.66, and from 0.28 to 0.90 for lint percentage.

Lint index, the weight of lint from 100 seeds, and seed index, the weight of 100 seeds, interact to determine lint percentage through the relationship.

\[
\text{Lint percentage} = \frac{\text{lint index}}{\text{lint index} + \text{seed index}}
\]

Lint percentage, while a somewhat biased component of yield, is less tedious to estimate than lint index. It can be estimated from large samples without the need to count seeds and is servicable in selection for yield because the trait usually correlates highly with fiber yield. Meredith (1984) gave heritabilities of 0.78 to 0.81 for lint index and 0.87 for seed index, indicating that either trait is readily selected.

Earliness, a measure of the time required for a cultivar to produce a satisfactory crop under the prevailing conditions, has received increased attention from breeders. Niles and Feaster (1984) pointed out that degree of earliness relates to various components, including rate of germination, days to first flower, rate of flowering, percentage of bolls retained, and maturation rate of bolls.

Although there is little precise knowledge of the inheritance of the components of earliness, they are manipulated readily through selection and can be changed separately or concurrently. More efficient management of pests and savings from reduced production costs over a shorter term are considerations in selecting for increased earliness. Niles and Feaster (1984) cautioned, however, that selection for precocity can be overstressed to the point of eroding yield potential and fiber quality.

Tolerance to environmental stresses has come under increasing attention in recent years. Niles and Feaster (1984) cited evidence of genetic variability for tolerance to salinity, heat stress, cold tolerance in seedlings, and drought. Feaster and Turcotte (1965) and Feaster et al. (1980) demonstrated that Pima cottons could be bred for satisfactory performance under nocturnal heat regimes varying from 18 to 30°C during July and August. Pima cultivars from a decade ago were closely adapted to the various temperature regimes, whereas modern materials are tolerant of all regimes where these cottons are grown.
The growth habit of cotton plants often relates to degree of precocity. Early cottons—cultivars producing a crop in as few as 140 days—are short statured and compact, whereas full-season cultivars grow taller and are more open in habit. Plant habit is readily selectable. Early cottons for stripping usually are bred with storm-resistant bolls and short limbs. Each trait depends mostly on a single gene for expression. Boll rots are a problem in some areas, especially highly humid areas like the lower Delta zone. Okra leaf-shape, a single-gene trait that imparts a narrow leaf lobe instead of the broad leaf lobes noted in most cultivars, allows for better penetration of sunlight and a less humid environment in the plant canopy, which is less suitable for development of boll rots.

Pima cultivars have been greatly modified in recent years with the objective of obtaining higher yields and better adaptation to spindle picking. Through inputs of new genetic variability from diverse sources, Pima cottons have become more nearly like full-season upland cultivars in plant form, boll size, and lint percentage while retaining the fiber properties expected of high quality G. barbadense cottons.

Fiber and Seed Traits

Cotton is cultivated mostly for fiber, and much effort has been invested in the improvement of this commodity. Traditionally, cotton lint has been evaluated by classers, who are experts in judging fiber quality by sight and feel. Classer’s staple length is a rough measure of fiber length given in inches, 1 to 1¼ inch the modal standards for upland, 1⅞ inch for Pima fiber, and 1⅜ to 1¾ inch for Egyptian. Classer’s grade is based upon the color, feel, and trash content of raw cotton and is assigned as a number, with the lower number representing the higher grade.

Beginning about 50 years ago, instruments were developed to provide more critical evaluations of fiber quality, and microspinning tests to assess yarn quality came into use. Some of the measures furnished by instruments are:

1. 2.5% span fiber length: the distance in millimeters spanned by the longest 2.5% of the fibers in a test specimen.
2. 50% span fiber length: the distance in millimeters spanned by 50% of the fibers in a test specimen.
3. fiber length uniformity index: 100 times the ratio of the 50% span length to the 2.5% span length.
4. tenacity: the effort required to break a flat bundle of fibers given in g of force.
5. micronaire: a measure of airflow through a compressed specimen of fiber that relates to fiber fineness and/or maturity.

Length, tenacity, and fineness traits generally have high heritabilities, and are readily selectable (Meredith, 1984). Some measures of fiber properties are correlated with each other and with certain agronomic traits. Fiber tenacity and elasticity are usually negatively correlated, and lint length and tenacity are often positively correlated. Fiber tenacity is negatively correlated with fiber yield in upland cotton, with estimates ranging from $-0.36$ to $-0.69$ (Meredith, 1984). The negative relationship between fiber tenacity and fiber yield has been ameliorated to some extent, at least in breeding lines and a few cultivars (Miller and Rawlings, 1967a; Cuip and Harrell, 1973). Micronaire is positively correlated with fiber yield in upland cotton.

Most agronomic and fiber traits of cotton are quantitative characters that are thought to depend for expression upon the concerted action of multigenes (Meredith, 1984). Although end use frequently defines cotton quality, a good general definition of desirability in an upland cultivar is earliness of maturity, high fiber yield, good retention of seed cotton in bolls, lint length of 1 1/3 inch classer’s staple (about 28 mm 2.5% span fiber length), tenacity above average (about 22 g), good elasticity, micronaire in the premium range (3.5 to 4.9), and ginned lint free of foreign matter.

The chemical composition of seeds of various accessions of *G. hirsutum* was determined by Kohel (1978). He found considerable variation for oil content. There have been no attempts, however, to use such variability in breeding programs. There has been much effort devoted to breeding glandless cultivars with a low gossypol content in seeds. Gossypol, a terpenoid aldehyde substance contained in cotton pigment glands, is toxic to nonruminant animals. Some glandless stocks are competitive with normally glanded cultivars in fiber yield (Niles and Feaster, 1984). Nevertheless, there have been few incentives for growers to replace glanded cultivars with glandless stocks.

**Insects and Pathogens**

In 1981–1982, about 16.1% of world cotton production was lost to insects and mites. Prominent among these predators were bollworms, the boll weevil, mites, leafhoppers, leaf worms, and plant bugs. Breeding for insect resistance promises to be an important component of programs for protecting cotton plants from insect pests (Ridgway et al., 1984).

Some insect resistance traits are simply inherited. One such character, nectarless, deprives nectar, a source of energy, from plant bugs and imagoes of bollworms. Other traits related to insect resistance are more
complex in inheritance, such as increased terpenoid aldehyde level in flower buds, which imparts resistance to bollworm larvae. Glabrous leaf, determined by one or more alleles, disrupts egg-laying by the imagos of bollworms. Cultivars with early and rapid fruiting escape much damage from insect pests, particularly from the boll weevil.

Although many insect-resistant characters are known, practical use of these has been limited. The most widely used are increased leaf pilosity, which provides resistance to leaf hoppers in the Old World tropics and subtropics, and nectarless in the U.S. Nectarless cultivars have been released, and these are increasing in popularity (Ridgway et al., 1984).

Several genes have been identified that impart resistance to bacterial blight, and numerous cultivars with complete immunity to all races of the pathogen have been developed in the United States and Africa. Levels of resistance to Fusarium wilt have increased progressively over the years. Part of the resistance to Fusarium wilt is related to increased resistance to nematodes, particularly the rootknot nematode complex, the nematodes creating wounds on roots that allow the wilt to enter. The Egyptian and Tanguis cultivars of G. barbadense are often highly resistant to Verticillium wilt, a vascular pathogen in regions with neutral to basic soils. These sources of resistance have been used to increase tolerance of upland cultivars to Verticillium wilt, however, such tolerant cultivars often suffer losses to the pathogen when cooler than normal temperatures prevail. Resistance to Verticillium wilt is regarded as the most important objective in cotton pathology breeding in the United States today (Ridgway et al., 1984; Niles and Feaster, 1984).

The following outlines important breeding objectives of various cotton producing regions of the world.

United States: Resistance to bollworms (Heliothis spp.), pink bollworm (Pectinophora gossypiella Saunders), white flies (Bemisia spp.), plant bugs (Lygus spp.), fleahopper (Pseudatomoscelis seriatus Reuter), boll weevil (Anthonomus grandis Boh.), bacterial blight [Xanthomonas campestris pv malvacearum (Smith) Dye], Verticillium wilt (Verticillium dahliae Kleb.), Fusarium wilt (Fusarium oxysporum sp. vasinfectum (Atk.) Snyder. & Hans.), cotton rust (Puccinia coccabata Arth. & Holw.), seedling diseases (mostly Pythium spp. and Rhizoctonia solani Kuehn), and root knot nematodes (Meloidogyne spp.). Increased fiber yield, earliness, better adaptation for machine harvest, adaptation to climatic adversities, and increased milling quality of seeds. Uniformity of fiber length, increased fiber tenacity, and micronaire in the premium range (3.5 to 4.9).

USSR: Resistance to Verticillium wilt and viral leaf curl. Increased fiber yield and quality.

India and Pakistan: Resistance to leafhoppers (Empoasca spp.). Increased fiber yield and quality.

Africa: Resistance to leafhoppers, bacterial blight, and viral leaf curl. Increased milling quality of seeds (Egypt). Increased fiber yield and quality.

Tropical America: Resistance to leaf worm (Alabama argillacea Huebner). Adaptation to climatic adversities. Increased fiber yield and quality.

Australia: Resistance to bollworm (Heliothis spp.). Better adaptation to local climates. Better fiber yield and quality.

STEPS IN CULTIVAR DEVELOPMENT

There are four basic steps in the development of modern cotton cultivars:

1. Visualizing the kind of cultivar needed.
2. Creating a breeding population that will yield the cultivar desired.
3. Selecting the new cultivar from the population.
4. Increasing seed of the new cultivar for release to growers.

Visualizing the Cultivar

New cultivars should meet certain minimum standards of performance. Fiber yield must not be lower than that of current cultivars, and fiber properties must be average or better. The cultivar should have a broad enough range of adaptation to ensure the marketing of profitable quantities of seed. Characteristics available for cultivar improvement are many, and these can be incorporated singly or in combinations.

Creation of Breeding Populations

Populations usually are developed by crossing germplasm stocks that incorporate the traits desired. Germplasm sources can be current cultivars, obsolete cultivars, and stocks released by genetic and breeding programs. Sometimes segregating populations are pedigreed directly from a single cross. Other programs intercross germplasm stocks for a few generations before selection commences. Sometimes a single gene or a few specific genes are transferred into a cultivar from one or more donor stocks.
Selecting the Cultivar

If the intent is to transfer a new gene to a cultivar, the breeder uses about five generations, attended by close selection for a return to the basic cultivar phenotype, to accomplish the improvement. In pedigree programs, as many as 10,000 individual plants might be evaluated in progeny rows. These are screened for most of the fiber and disease resistance properties desired, and the best are saved for seed increases for yield evaluation. Yield trials are conducted in replicated tests over as broad an area as possible. The best yielding progenies with the desired fiber and disease and insect resistance properties are commonly bulked to form a new cultivar.

The breeding of cotton usually commences under open-pollinated conditions, and that, along with the bulking of sister lines, allows for the possibility of residual heterogeneity within the component lines, as well as genetic heterogeneity among the lines. The extent, however, of such heterozygosity and heterogeneity within a cultivar remains unknown.

Increasing Seed of the Cultivar

Once the new cultivar is selected, the seeds are multiplied in increase blocks, often under contract with cotton growers. The resulting seeds are prepared carefully for planting by delinting, grading, and testing for germination. These seeds are designated breeder seed and are sold to selected growers for the production of foundation seed. Foundation seed is used to grow registered seed for commercial cotton growers. The certification process encompasses all aspects of seed increase for recognized cotton cultivars and is a statement of cultivar purity, seed quality, and freedom from foreign matter. Cotton planting seed is commonly grown in arid regions to avoid weather damage and ensure maximum seed quality.

SOURCES OF GENETIC VARIABILITY

Types of Parents and Populations

The cultivated cottons are in the family Malvaceae, tribe Gossypieae, and genus *Gossypium*, which contains about 38 species distributed in the semi-arid tropics and subtropics of the world. The tribe Gossypieae contains other genera, but there is no evidence that any of these are capable of germ-plasm exchange with *Gossypium* using conventional means of hybridization (Fryxell, 1979). Fryxell recognized 6 tetraploid species of *Gossypium* and 32 diploids. Artificial polyploids can be created from the
diploids or from crosses between cultivated tetraploids and certain of the
diploids, and these have proved useful for transferring germplasm from
the diploids into the tetraploids. Also, the tetraploid species cross readily,
and there is at least limited exchange of germplasm among these.

The following are sources of germplasm available in the United States
for the improvement of tetraploid cottons: (a) obsolete cultivars of *G. hirsutum*
maintained at the Delta Branch Research Station at Stoneville,
Mississippi; (b) obsolete and primitive stocks of *G. barbadense*, main-
tained at the USDA Cotton Research Center, Phoenix, Arizona; and (c)
primitive stocks of *G. hirsutum* and cultivated and wild diploid species
maintained at the USDA Cotton and Grain Genetics Laboratory, at
College Station, Texas.

Obsolete cultivars might be used directly in breeding programs. Ger-
mlasm from diploid and primitive tetraploids species usually is processed
through basic genetic and breeding programs which identify potentially
useful genes conferring superior properties and transfer these to back-
grounds more suitable for practical breeding scheme. Most basic breeding
programs are conducted by public agencies.

Characters from germplasm sources that have been successfully used
in commercial breeding programs include: (a) bacterial blight resistance
from obsolete cultivars and primitive stocks of *G. hirsutum* and from *G.
arboreum*; (b) increased lint strength in upland cotton from *G. thurberi*
Tod., a diploid cotton native to Arizona; (c) glandless (low gossypol) seed
from ‘Hopi’, a primitive cultivated stock of *G. hirsutum*; (d) glabrous
plant from *G. armourianum* Kearn., a wild American diploid taxon, and
from primitive stocks of *G. hirsutum*; (e) increased terpenoid aldehyde
levels in flower buds of upland cotton from primitive stocks of *G. hirsu-
tum*; (f) increased yield in *G. barbadense* from upland cottons; and (g)
cytoplasmic male sterility and restorers from *G. harknessii* Brand., an
American diploid taxon.

Population Development by Hybridization

In North Carolina during July, cotton flowers open and commence shedding pollen around 0900 hours, usually after ambient shade temperature rises to 27°C. Once open, flowers are receptive to pollination for 8 hours or less. Once the flower is pollinated, the corolla closes and dehisces the afternoon of the following day.

Cotton flowers are ready for emasculation by noon the day before anthesis. Some workers emasculate cotton flowers with the fingers, removing the petals and androecium in one deft operation. Cutting the petal away with an emasculating device, followed by stripping the
anthers, is less injurious to flowers and improves fruit sets. Stigmas of
emasculated flowers can be treated with a 30% ethanol solution (aqueous)
to kill extraneous pollen. After emasculation, the stigma is fitted with
some protective device, such as a length of soda straw (Fig. 5-3). Flowers
to be used as a pollen source are sealed with a protective device, such as a
paper clip (Fig. 5-3).

Emasculated flowers are pollinated the day following emasculation,
usually beginning around 1000 hours in North Carolina. The pollen is
applied directly from the anthers of the female parent to the stigma of the
male parent, usually within minutes after the male flower is collected.
After pollination, the protective device is replaced and the flower tagged
according to some preplanned system of identification. Rate of fruit set
after pollination of emasculated flowers varies with location, season, and
cultivar, and can vary from 50 to 90% for upland cottons in the field and in
greenhouses, but usually is less with G. barbadense (Lee, 1980).

Basic genetic and breeding programs use artificial crossing and selfing
through all phases of development from making the initial crosses until
breeding lines are selected and evaluated for release. Most commercial
breeding programs use artificial cross-pollination only in the initial stages
of mating breeding lines. Progeny rows and yield trials from which superi-
or lines are selected are grown under conditions of open pollination.

Panmictic populations have been used in efforts to change adverse
linkage relationships in cotton. Plants in such populations are routinely in-
tercrossed each generation to provide seed for the ensuing generation.
Examples of such populations are those used by Miller and Rawlings
(1967a) to change an adverse relationship between lint tenacity and fiber
yield in upland cotton, and by Lee (1948) to change linkage relationships
between glabrous leaf, low lint percentage, and short lint. Miller and
Rawlings (1967a) suggested the use of natural crossing for intermingling
gene pools where pollen vectors, mostly wild bees, are abundant.

Mutagenesis

Although mutagens have been of value in cytogenetic work in cotton, par-
ticularly for the production of chromosomal aberrations, reports of mu-
tagens producing characters of potential economic worth are rare. The
best known is the induction of a glandless (low gossypol) mutant following
the treatment of seed of the Egyptian cotton cultivar 'Giza 45' with
32 P (Affifi et al., 1966). The chief value of the Egyptian mutation, from
the standpoint of breeding, is that the new allele, when homozygous, im-
parts glandlessness, whereas the combined action of alleles at two loci
are required to determine glandlessness of the Hopi (American) type.
BREEDING PROCEDURES

Mass Selection

Mass selection, the taking of superior individuals from existing populations and using the increase from these without testing, must be virtually as old as cultivated cottons and was the prevailing method of cotton breeding through the nineteenth and early twentieth centuries (Brown and Ware, 1958). An early example of mass selection in upland cotton was the work of C. M. Vick of Warren County, Mississippi, between 1830 and 1837 (Moore, 1956). Vick set out to improve the 'Petit Gulf' cultivar by selecting superior plants, a technique that had been used successfully by maize and wheat breeders. The result was an advance in fiber yield, but Vick was not satisfied. In 1834, Vick examined lint taken from selected plants, and immediately noted substantial differences in what he had considered to be uniform stocks. Through selecting for both superior lint and plant performance, Vick produced a cultivar called 'Hundred Seed,' a cotton that immediately commanded a premium on the New Orleans market. Vick is usually credited with inaugurating the concept of multicharacter selection in cotton.

Mass selection without subsequent testing is not used in cotton improvement today, except as a tool of cultivar maintenance. Maintenance can vary from periodic roguing of off-types to rigid reselection and testing with the expectation that there will be an improvement in the cultivar as a result of reselection.

Pedigree Selection

Modern cotton cultivars are selected from existing cultivars, from crosses between cultivars, or from gene pools developed from intercrossing germplasm stocks from diverse sources. Progeny lines are pedigreed from initial selections, whether these are individual plants or bolls, and the better progeny rows are often bulked to form a cultivar. Selections for evaluation and increase usually are made at the $F_5$ to $F_4$ generation. Selecting, testing, seed increase, and cultivar maintenance are performed under open-pollination but frequently in semi-isolation. There are several variations of the pedigree technique of breeding, each designed to fit what is perceived to be a special set of needs. Three such variants will be discussed in detail: the mass-pedigree technique, the multiadversity resistance (MAR) breeding program, and the California Acala breeding program.
The Mass-Pedigree Technique. Mass-pedigree is a term applied by S. C. Harland to describe a program of mass selection followed by rigid selection of lines pedigreed from individual plants (Brown and Ware, 1958). The Tungus crop of Peru had become badly contaminated by 1940, and Harland was commissioned to restore the cultivar to the qualities being lost. He began by selecting single bolls from 22,000 plants throughout the region where the crop was grown. Screening for fiber quality reduced these to 2863 plants, the seed from which were planted in short progeny rows. Only 41 of the rows were saved. A total of 200 plants were selected from the 41 rows and the progeny of the 200 plants were evaluated in ten replications, and 41 lines were selected. The best five lines were retained for increase and further selection, whereas the remaining 36 were bulked to provide a seed increase for growers. Thereafter, seed for release to growers was provided from bulking the better progeny rows from the continuing program. All of the work was performed under open pollination.

Mass-pedigree is used in the United States today by commercial cotton breeders. Examples of successful upland cultivars mass-pedigreed from older stocks are the ‘Stoneville’ series of upland cultivars (Niles and Feaster, 1984). These originated, beginning in 1916, from the ‘Lone Star’ background. A recent cultivar from the lineage is ‘Stoneville 213’ selected from ‘Stoneville 7A,’ which in turn was selected from ‘Stoneville 2B.’ The mass pedigree method simultaneously provides for maintenance of a cultivar and the opportunity for genetic improvement.

The Multiaversity Resistance Breeding Program. The multiaversity resistance (MAR) concept of cotton improvement, as described by Luther Bird of Texas A&M University, dates back to procedures introduced in 1963 which challenged cottonseed with a combination of pathogens and ambient temperatures likely to be experienced at planting. The program grew to incorporate many adversities confronting the cotton crop, from pregermination to harvest. These include ability to withstand low temperature after planting, resistance to seedling diseases, resistance to bacterial blight, resistance to insects, and earliness of maturity. The SP, CAMD, and MAR groups of cultivars, successive products of the program, are currently planted on about 34% of the cotton hectarage in Texas (Bird, 1982).

A cycle of selection is initiated in the fall after seeds have been harvested from the germplasm nursery, a population grown yearly into which there are frequent inputs of genetic variability. Acid-delinted seeds are placed in open agar plates in a field laboratory so that the plates can become naturally infested with the spores of seed molds, mostly Alternaria and Fusarium spp. The plates are covered, placed in chambers, and held at 14°C for 8 days. At the end of the cold treatment, the plates are removed and the seed scored for resistance to infection.
Seeds free of mold and with radicles no longer than 1 mm are saved for additional screening. The surviving seeds are placed in a greenhouse in cups of soil naturally infested with seedling diseases, mostly *Pythium* spp. and *Rhizoctonia solani*. After the cotyledons have expanded, each plant is infested with various races of bacterial blight through a scratch on the underside of one of the cotyledons. Fourteen days later, the seedlings are evaluated for resistance to blight and are checked for lesions of damping off at the soil line. The seedlings that survive the second set of tests, usually about 2400, are transferred to greenhouse pots for seed increase.

The seeds from the winter greenhouse plantings are harvested, and individual plant progenies are evaluated in single rows at one location. The rows are challenged with inoculum containing four races of bacterial blight, and susceptible plants are discarded. Through the remainder of the growing season, the plants in the rows are evaluated for earliness, fruiting rate, boll characteristics, and lint percentage. Usually about 250 progeny rows survive the first summer of evaluation. Boll samples are collected at random from the surviving rows, the seeds are delinted and the progeny are subjected to another round of cold and pathogen tests.

The survivors of the second round of winter tests are sorted according to minimum fiber quality standards. The 140 to 150 progenies that usually survive are given line designations, and are subjected to various disease and insect challenges under field conditions. The approximately 40 lines that survive these tests are evaluated for performance during the third summer in replicated trials at various locations in Texas. The lines that survive the performance trials are bulked according to preconceived type designations, and the bulks are used in further testing under field conditions. The bulks are released as cultivars if any of them show superior performance in the final trials.

Expectations within the MAR program are based on maintaining and adding to past achievements. Thus, the MAR program is evolutionary in the sense that there is room for modification without loss of gains. The MAR program differs from most breeding programs in that natural selection is deliberately exploited where appropriate, and use is made of the interrelationships among genes for resistance. For example, resistance to bacterial blight shows a strong association with resistance to *Fusarium* wilt and lesser, but significant, associations with resistance to *Verticillium* wilt, root rot, and seed-coat resistance to molds. A reduced rate of germination at 13º to 18ºC is associated with resistance to *Verticillium* wilt and resistance to seedling pathogens. Seed-coat resistance to molds is strongly associated with earliness and high fiber yield. These associations form a complex relationship that has been verified by multiple regression and 15 years of practical experience.

From time to time, genes for new characters are added to the MAR germplasm pool. These determine resistance to cotton insects and
diseases and control morphological characters, such as okra leaf shape, fregio bract, glabrous plant, glandlessness, and nectarless. These traits serve as harvest aids, impart insect resistance, or improve the milling quality of seeds. New traits are not selected for in the MAR program until the relationships of these with existing traits of importance have been determined.

*The California Acala Breeding Program.* The Acala cottons are a unique group of upland cultivars adapted for production under irrigation in the Western adaptive zone of the United States. Acala cottons feature excellent fiber length and tenacity, satisfactory yield under full season growth, and often marked tolerance to Verticillium wilt.

High-quality Acala cotton for production in the San Joaquin Valley of California dates to ‘Acala 4-42,’ which was bred by George Harrison of the USDA-ARS and released in 1949. Since 1978, H. B. Cooper and his associates have continued breeding Acala cottons for the California Planting Cotton Seed Distributors, a growers’ cooperative. The continuing objectives are the development of high-yielding cultivars with improved fiber and seed properties. Traits under selection are earliness, tolerance to Verticillium wilt, maintenance of fiber length (2.5% span) length of about 29 to 30 mm), fiber-length uniformity and high tenacity (about 24 g), reduction in neps (knots in yarn) and spinning waste, increased oil and protein in seeds, and decreased gossypol in seeds. Figure 5-5 outlines the breeding program (Cooper et al., 1984).

The first step in breeding a new cultivar is to introduce parental stocks from wherever available, including germplasm releases, accessions from world collections, and obsolete and current cultivars. The parental stocks are intercrossed, and the segregates reselected until stable lines with the desired traits are obtained.

The second step is the setting up of the applied breeding program, which is based on pedigree selection (Fig. 5-5). The lines selected in step 1 are intercrossed to obtain 50 to 75 F₁ progenies. F₂ segregates from these crosses are selected on the basis of how well these combine the traits desired. F₂ progenies from the selected F₂ plants are increased as progeny rows where visual selection is practiced for agronomic traits, including disease resistance, lint percentage, seed size, and lint properties. Plant selection within desirable rows, followed by progeny row evaluation, is performed through the F₃ generation. At the end of this phase of the program, the best F₃-derived lines in the F₃ generation are harvested. The selected lines are planted in four replications at each of two locations in yield trials, one on soil free of Verticillium wilt and the other on soil infested with Verticillium wilt. The lines are evaluated visually and through measurement of agronomic and fiber traits.

The lines in the first replicated yield trial that perform better than the
check cultivars are planted in preliminary strain tests in four replications at each of three locations, one in the northern end of the San Joaquin Valley, one in the southern end, and one on soil heavily infested with Verticillium wilt. The lines are evaluated for the same traits as in the first yield trial. In addition, fiber samples are taken from the top yielders for comparison in microspinning tests.
The most promising lines from the preliminary strains test are planted in advanced strains tests in four replications at seven locations. Micro-spinning tests are performed on two replications per location and fine-yarn spinning tests are conducted on lint from three locations. Seed samples are collected from the best lines and analyzed for oil and gossypol content.

An ancillary activity that seems unique to the California Acala breeding program is that seeds are increased for each line entered in the first yield trial. If any of the lines should become eligible for release as cultivars or components of cultivars after 3 years of testing, there will be available in cold storage at least 5 metric tons of seed of each. The most recent product developed from the system outlined in Fig. 5-5 is ‘Acala SJC-1,’ a cultivar that is replacing earlier releases. ‘Acala SJC-1’ embodies most of the objectives of the program outlined earlier.

The applied breeding phase of the California Acala program is illustrative of the pedigree selection and testing methods used by many breeders of upland and extra-long-stapled cotton. The use of complex germplasm pools from which to make the initial selections is less widespread, but is increasing, particularly in programs where the initial germplasm base available cannot supply the agronomic and fiber characteristics needed. Culp and Harrell (1973) used a complex genetic base for upgrading fiber quality in upland cottons adapted to the eastern zone of the United States, and Feaster and Turcotte (1965) and Feaster et al. (1980) used a wide range of \( G. \ barbadense \) and \( G. \ hirsutum \) stocks in breeding Pima cottons. The objectives have been adaptation for a wide range of altitudes and temperature regimes, and increased fiber yield from the improvement of fiber yield components.

**Backcross Method**

The backcross method of breeding is useful for transferring discrete genetic characters into cultivars. The method seems particularly suited for the incorporation of genes for disease resistance. The assumption is that, except for the introduced genes, the genotype of the recurrent parent will be recovered. Theoretically, selection for other than the introduced genes is not required.

Knight (1954), working in the Sudan, used backcrossing to incorporate into Sakel cotton (\( G. \ barbadense \)) genes for resistance to bacterial blight and leafhoppers. Knight modified the usual backcross procedure in that he selected rigorously for agronomic and fiber traits as the backcross generations progressed.

Most often when backcrossing is used with cotton, the modified tech-
nique of Knight is the method of choice. One or more characters are introduced through backcrossing. The breeder selects for any new and favorable combinations that might arise during the backcross generations. The modified backcrossing scheme allows for the incorporation of multigenic characters of a quantitative nature, as well as for genes conferring discrete variability.

Modified backcrossing is frequently used to prepare germplasm for introduction into breeding populations. Culp and Harrell (1973) used the technique to introduce lint tenacity genes into their breeding populations, and Bird (1982) used backcrossing to introduce new genes into the MAR program.

There is evidence that the introduction of germplasm from exotic sources, such as certain diploid species, and primitive stocks of *G. barbadense* and *G. hirsutum*, often results in the retention of linkages detrimental to agronomic performance. Lee (1984) reversed adverse effects on lint percentage and fiber properties associated with the Sm2 (smooth leaf) allele through a combination of backcrossing, random intercrossing of segregates, and pedigree selection.

**Index Selection**

A selection index has been defined as the linear combination of observations needed to compute a criterion for selection. Miller et al. (1958) constructed selection indices for upland cotton based on estimates of genetic variances for agronomic and fiber traits and covariances among the traits. For fiber yield, they predicted that various indices using lint yield and yield-related components, such as lint percentage, bolls per plant, and seed index, could be useful in selecting for higher yield.

Manning (1956), working in Uganda, indexed yield components in an attempt to increase yield of the upland cultivar, ‘BP-52.’ The scheme sought to simultaneously maximize bolls per plant, seeds per boll, and weight of lint per boll. Based on data taken on the individual components through 11 generations of selection, the expected accumulative advance in fiber yield was estimated as 44%. There was an actual advance of about 30% over 13 generations and most of that was accounted for by an increase in lint per boll from 1.34 g per boll at generation 1 to 1.67 g at generation 13.

Other than Manning’s efforts, there is no evidence that selection indices have been used in cotton breeding programs. The chief difficulties with indices are that the data taken from a given population are probably not valid for other populations, and indexing each population considered for improvement is costly and time consuming.
FIELD- PLOT TECHNIQUES FOR GENOTYPE EVALUATION

Lint cotton yield is the trait of greatest interest to cotton growers, and the most costly for breeders to evaluate. That is because heritability estimates for fiber yield generally become more reliable with the expansion of testing, and there is the need to evaluate the interaction of new strains with environments (Miller et al., 1958). Therefore, the breeding and testing of a new cultivar requires field plot work.

The preliminary choices in any cotton breeding program are a group of promising plants. These might stem from selecting within a heterogeneous cultivar, or from a segregating population following the cross of cultivars or other germplasm sources. Although reasonable estimates of some yield components such as lint index and fruit size can be made from single plants, the heritability of fiber yield estimated on a per-plant basis is virtually zero (Meredith, 1984). Therefore, yield comparisons must be made on larger populations stemming from each of several plants.

The number of plants selected for preliminary evaluation and seed increase can range from the hundreds to the thousands. The seed from these are planted in progeny rows, usually one row per plant, on uniform land, and in as compact a design as possible. Although the length of such rows is variable, 15 to 20 m is commonly used.

Visual selection eliminates most of the progeny rows. Fiber evaluations might be done on progeny rows, but such tests are usually delayed to the second step. The surviving progeny rows are harvested separately and the seeds are used to plant a local trial, usually of about four replications in a randomized complete-block design. Both visual selection and statistical evaluation are routinely used in culling the lines further. Such a test might be repeated for 1 year for further evaluation and seed increase.

Once enough seed has been accumulated, replicated field tests are performed over the geographic area in which the prospective cultivar is expected to be grown. Such tests usually contain four to six replications of plots 15 to 20 m in length planted as randomized complete blocks. These tests are evaluated for agronomic traits, especially fiber yield, fiber properties, and interaction of the component strains with environments. Strains that show evidence of local adaptation are discarded and further tests are performed with the survivors. After 3 years of testing, seed harvested from the highest yielding lines with acceptable fiber properties and evidence of broad adaptation might be pooled and the seed increased as a commercial cultivar.

A plot in a yield trial commonly consists of four adjoining rows, the outside rows serving as buffers or guards. Only the inner pair of rows is harvested, and harvest usually is performed with a multirow spindle picker or stripper equipped with a device for bagging the cotton from individual plots (Fig. 5-6). After weighing, a subsample of the harvest from a
plot is used for estimating lint percentage and fiber properties. The samples are ginned on microgins equipped with lint-cleaning devices. Usually, only two plots per location are evaluated for fiber and seed properties.

There are beltwide tests of cultivars and new strains performed in the United States today. The cultivar tests evaluate, on an ongoing basis, currently used cultivars of *G. hirsutum* and *G. barbadense* in adaptive zones across the United States. In addition, tests are conducted on new strains of high-quality upland cotton in the Delta and eastern zones. The results
of these tests are published yearly by the USDA-ARS. In addition, public and private cotton breeders and geneticists perform trials on short-season strains and cultivars and on insect-resistant strains in various adaptive zones. The designs of the tests in all public trials are the same as those used for yield trials and fiber quality evaluations by commercial breeders.

PROCEDURES FOR SEED PRODUCTION

Methods for Producing and Maintaining Breeder Seed

In cotton breeding, multiplication and maintenance of seed stocks is vital to the success of a given cultivar. Once a new cultivar is selected, the breeder increases seed to the volume required for the production of foundation seed. A portion of breeder seed is reserved for cultivar maintenance. This amount is about 5 metric tons in the California Acala breeding program (Cooper et al., 1984).

After a cotton cultivar is released, consideration must be given to maintenance of the traits that make the cultivar commercially competitive. There are programs designed to maintain or even improve cultivars. These were outlined by Niles and Feaster (1984).

If the objective of the breeder is to maintain a cultivar without genetic change, one technique is to store ample breeder seed under refrigeration, from which portions can be withdrawn for periodic increases. This method is used by Cooper et al. (1984) to maintain the genetic standards of Acala cottons while new cultivars are being bred.

Other procedures of maintenance involve selection. Growing the cultivar and roguing plants that do not conform to the cultivar type is the most simple form of maintenance. Modern breeders, however, are less interested in maintaining type than in increasing the utility of a cultivar while preserving some semblance of type. The modal bulk method of Manning (1956) conforms roughly to maintenance methods used by most American cotton breeders. Individual plants are selected and evaluated for yield components and fiber properties. Seeds of plants that survive selection are pooled for further propagation. Progeny row evaluation can be fitted into the modal bulk method. Seeds of the better rows can be bulked or maintained separately for further increase and evaluation. The modal bulk system not only provides maintenance of a cultivar, but offers the opportunity for an increase in performance.

Selection in a maintenance program is based on the assumption that a population derived from a segment of the cultivar will be equal or superior in performance to the unselected cultivar. There are risks, however, in reselection. The genetic base of the population can be narrowed and re-
sidual heterozygosity can be reduced. Also, the buffering capacity of the cultivar to adapt to fluctuations in the environment can be destroyed. Meredith and Culp (1979) showed, however, that a group of modern cultivars remained remarkably stable for yielding ability over a diversity of environments. That finding suggested that the cultivars carried considerable genetic heterogeneity and heterozygosity, and that maintenance had been effective.

**Commercial Seed Production and Marketing**

Approximately 13.5 kg of seed are required for planting 1 ha of cotton. Therefore, about 65,000 metric tons of planting seed are needed annually to plant the American crop of between 4 and 5 million ha. Nine or ten years are required to bring a new cultivar from the initial steps of breeding to entry in the seed market, the last two or three involved in increasing seed through the various classes leading up to commercial sales. Breeders seed is usually the product from bulking the lines that survive the evaluation processes in developing a new cultivar. These might be further increased before being released to contract growers for the production of foundation seed. Foundation seeds are used to produce the first generation of registered seed, a class offered for sale to commercial growers and for further increase of commercial seed. Foundation and registered seeds are commonly grown in arid areas to ensure a good quality product.

The classes of seed are certified by agencies in the various states vested with authority by state laws. These can be crop improvement associations, agencies within state agricultural institutions, or boards of prominent citizens with interests in agriculture. The classes of certified cotton planting seed recognized by the North Carolina Crop Improvement Association are breeder seed, foundation seed, and registered seed. Registered seed is a class for which the generation from breeder seed is printed on the label. Registered seed may be sold for commercial planting or for the production of additional generations of registered seed.

All classes of seed for certification must be grown in fields that are free of weeds; the seed cotton must be harvested and carefully ginned; and the seeds must be delinted, dried, and graded on a gravity table to remove broken seeds, groats (naked embryos), and seeds with poorly developed embryos. All certified classes of seed are labeled as to cultivar, class, purity, and germination potential.

Under humid conditions, cotton seeds lose viability in about 2 years. Under cold storage of $-7^\circ$C, good-quality seed can retain viability for 10 or more years. Small lots of seed of breeding lines and genetic stocks usually are stored under refrigeration. Breeder seed sometimes is stored
under refrigeration, as is the case with the California Acala breeding pro-
gram (Cooper et al., 1984).

FUTURE PROSPECTS FOR CULTIVAR DEVELOPMENT

Cotton is a crop that is predominately self-pollinated, and most of the
genetic variance for economic characters is of the additive type (Meredith,
1984). Thus far, pedigree selection has proven effective for breeding su-
perior cultivars. Meredith and Bridge (1984) showed an increased rate in
potential yield of new cultivars and advanced lines adapted for produc-
tion in the Delta and eastern zones of the United States of 11.4 kg/ha/yr
between 1961 and 1980. Therefore, the breeding methods used today
are likely to persist for the foreseeable future. There are some methods
that have potential as adjuncts to the traditional methods of cotton breed-
ing.

Hybrids

There has been much attention devoted to development of hybrids in cot-
ton. However, there has not been any significant commercial production
of cotton hybrids in the United States to date. Lee (1983) reviewed the
genetic potential for hybrids in cotton and concluded that much of the het-
erotic effects detected earlier by various workers, as high as 40% more
fiber yield than the best parent in a few crosses, are being fixed by breeder.
Meredith and Bridge (1984) showed that genetic improvement of
upland cotton in the United States advanced at the rate of 7 kg/ha/yr
of fiber during the 1960s and 1970s. Moreover, the highest yielding
hybrids have come from crosses among the best cultivars. Therefore, a
hybrid cotton program would need to be accompanied by a successful
program of conventional cotton breeding. An alternative method would
be to use the cultivars developed by other breeders.

The most daunting challenge confronting the production of hybrid
cotton seed is the mass transport of cotton pollen. Cotton pollen is natu-
really vectored only by insects, and marshalling the numbers of such in-
sects required for seed production seems a formidable undertaking.

About 250,000 ha of cotton hybrids are grown annually in India,
much of this being F₁ hybrids between G. hirsutum and G. barbadense.
Seeds are produced by hand pollination using recessive genetic male ste-
tility. In this system, only one-fourth of the plants in the female line are
useful. The fertile plants are rogued, and pollen from male rows is applied
to unguarded stigmas on the male-sterile plants. Plants in production
fields are commonly spaced 1 m apart, and fields are ratooned for two or
more seasons. The production of cotton hybrids in India is a labor intensive enterprise that would seem to have no potential in the United States.

Recurrent Selection

Recurrent selection programs presume to increase the frequency of desirable alleles through a process of detecting the better members of a population and intermatting these to form a new population. An example of recurrent selection applied to a cotton population was reported by Miller and Rawlings (1967b). F₁ plants of a cross between two upland cotton lines, one selected for high fiber yield and low fiber tenacity, and the other for low yield and high tenacity, yielded 13% more fiber than the better parent. The F₁ of the cross was advanced to the F₃, and 81 F₃ plants were taken at random and increased by bulk self-pollination to the F₅ and F₇ generations. The lines were grown in two replications at each of two locations to detect the six highest-yielding lines. These formed the basis for three cycles of recurrent phenotypic selection according to the scheme outlined in Table 5-3. Significant increases in fiber yield were recorded for each cycle of selection. Yields of the third-cycle selection exceeded the

Table 5-3  Procedures Used by Miller and Rawlings (1967b) for Recurrent Selection for Fiber Yield in Upland Cotton

<table>
<thead>
<tr>
<th>Step</th>
<th>Breeding Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The $F_4$ and $F_5$ generations of 81 lines were evaluated in two replications at each of two locations. The 81 lines were designated collectively as the cycle 0 population.</td>
</tr>
<tr>
<td>2</td>
<td>Remnant seed of the six highest-yielding lines in the $F_4$ and $F_5$ tests were planted, and the 15 possible single crossing among the lines were made using at least 10 flowers for each cross. The 15 single-cross populations were designated collectively as the cycle 1 population.</td>
</tr>
<tr>
<td>3</td>
<td>Six plants were taken at random from each of the 15 populations to produce seed for progeny tests. A total of 86 progenies were obtained, and these were tested in three or four replications at each of three locations.</td>
</tr>
<tr>
<td>4</td>
<td>The six highest-yielding lines out of the 86 were selected and intercrossed as in step 2 to form the cycle 2 population.</td>
</tr>
<tr>
<td>5</td>
<td>Six random plants from each of the 15 single-cross populations were selfed and the progenies were tested in two or three replications at each of three locations.</td>
</tr>
<tr>
<td>6</td>
<td>The six highest-yielding lines in the cycle 2 population were selected and intercrossed to form the cycle 3 population. The procedures described above were repeated for each cycle of selection.</td>
</tr>
</tbody>
</table>
average of the parental lines by 29.7% and the higher parent by 13.0%.
Selection was only for increase in fiber yield, and probably as a result,
fiber quality did not measure up to desired standards.

Recurrent selection programs for the production of populations from
which cultivars might be pedigreed will have to take into consideration
the need for multicharacter selection. Recurrent phenotypic selection
remains a potentially useful scheme for cotton breeders, one that prom-
ises to preserve a high level of genetic variability in the population as the
characters being selected are improved.

The techniques used to prepare germplasm for subsequent selection
in some pedigree breeding programs resembles recurrent phenotypic
selection without the formal testing procedures used by Miller and
Rawlings (1967a). Gilbert and Burdett (1984) mentioned that recurrent
phenotypic selection is used in the breeding of Deltapine cottons in the
western adaptive zone, but gave no details.

Production of Homozygous Lines

The evidence at hand suggests that cotton cultivars frequently are not
pure lines. However, pure-line selection has potential usefulness in cotton
breeding, particularly for standardizing certain fiber traits. There are
various ways to produce pure lines of cotton. Several generations of self-
ing has been used, but the technique is labor intensive and time consum-
ing. Doubling the chromosome number of haploid plants with colchicine
provides instantaneous pure lines. Unfortunately, haploids arising as one
of a pair of twin seedlings are rare.

The use of semi-matings provides virtually unlimited opportunities for
producing haploid tissues of any type of cotton (Turcotte and Feaster,
1967).

A genetic line of Pima cotton was found to be homozygous for an
allele that causes the failure of the union of the egg and sperm nuclei in as
many as 20% of fertilized ovules. Instead of uniting, the egg and sperm
nuclei give rise to independent, haploid tissue lines in the embryos devel-
oping from eggs in which no zygote forms. The resulting plant is a mosaic
of maternally and paternally derived tissues.

If the mother plant has an appropriate genetic marker, such as vires-
cent yellow plant color, the tissue lines derived from the egg and sperm
nuclei can be recognized, and the chromosome number of the desired tis-
sue doubled to produce a homozygous individual. Using semi-mating, patern-
nal haploid G. hirsutum tissues can be grown from G. barbadense ovules,
the resulting seedling being mosaics of G. hirsutum and G. barbadense
tissues.
Evolutionary Breeding

There has been some attention devoted to the use of evolutionary breeding for cereal crops. There has been less interest in the method among cotton breeders, perhaps because cotton is grown in rows where individual plants have considerable space in which to develop and produce a crop. Nevertheless, individual plants of cotton do compete, and the question arises as to whether or not the better competitors in the heterogeneous cultivars that are grown today would produce superior cultivars.

Quisenberry et al. (1978) crossed five diverse lines of upland cotton in all possible combinations and grew the progenies at Lubbock, Texas. $F_2$ seeds were collected from individual plants and the seeds mixed in about equal proportions. Ten successive generations were grown in a bulk plot without artificial selection, and a portion of the seed from each generation was stored for future evaluation. At the end of the natural selection phase, seed of all the generations were grown in one environment to equalize the vigor of the various lots. With generations as entries, a replicated test was performed in 1 year. There was a significant increase in fiber yield over generations. Seed number per meter of row increased, and seed size decreased. There were decreases in fiber length and tenacity, and an increase in micronaire. The authors concluded that evolutionary breeding had potential for improving cotton for growth in the suboptimal environment of the High Plains zone, which has a short season and limited rainfall.

Feaster et al. (1980) compared progress from natural and artificial selection of a heterogeneous population of Pima cotton at various altitudes in the southwestern United States. The criterion for selection was the height of the lower limits of the fruiting zone of individual plants. An optimum fruiting height correlates with high fiber yield. Differentials were most obvious at lower altitude, but at all sites the yield potential increased with both artificial and natural selection. However, artificial selection was much more effective than natural selection at all altitudes. Nevertheless, the authors concluded that the undisturbed bulks would eventually be naturally selected to maximize fiber yield, perhaps more rapidly at the lower altitudes.

Genetic Engineering

There is a growing tendency to describe plant breeding in general as genetic engineering. More particularly, however, the term is reserved for futuristic techniques which expect to insert specific genes or groups of genes into the genomes of cells which are then regenerated into plants.
There is much basic research underway aimed at genetically engineering cotton cultivars. Success recently was reported in regenerating explants from vegetative tissues of Acala cotton (Mitten, 1985). When such techniques become readily available with cotton species, the germplasm from genera related to *Gossypium* and from certain species within *Gossypium* offer the potential for increasing resistance to insects, pathogens, and herbicides. One goal of modern plant breeders that might be aided by genetic engineering techniques is the production of cotton plants with high levels of terpenoid aldehyde substances in foliage and flower buds, but little or none in seeds. Such cottons would resist many insect pests, but still have high-quality seeds for milling purposes. The desired genes are found in Australian diploid species of *Gossypium*, taxa that have chromosomes that do not pair readily with those of cultivated cottons.

REFERENCES


