Chapter 17

HOST PLANT RESISTANCE

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INTRODUCTION

Germplasm resources available to researchers include wild species of *Gossypium*, obsolete cultivars (varieties), current cultivars, germplasm released by public research scientists and the wild or feral extra long staple cotton *Gossypium barbadense* L. and upland cotton, *Gossypium hirsutum* L., collections.

Resistance of cotton to insects, diseases and nematodes is relative, i.e., variation in response is evident among almost any diverse group of germplasm one chooses to investigate. Most researchers use some type of accepted cultivar as a control in their experiments and only report a strain as being resistant when it receives significantly less damage than the control cultivar. Host plant resistance is one component of the production system for cotton. The cultivar becomes the foundation upon which all other components of the crops production and pest control systems operate. Thus, relatively small differences in genetic potential between cultivars can become important.

Early research in Africa led to the development of hirsute (hairy) cultivars of cotton to resist jassids (leafhoppers, *Empoasca* spp.). Painter (1951) provides an excellent discussion of early development of leafhopper resistance. The development of leafhopper resistant cultivars of cotton in South Africa and later in India offer the first instance of using resistant cultivars of cotton to control a major pest (Parnell, 1925; Hutchinson, 1962). The growing of very hairy cottons essentially eliminated leafhopper as major pests of cotton in tropical Africa.

The boll weevil, *Anthonomus grandis grandis* Boheman, moved into the United States Cotton Belt in 1892. Early cotton breeders responded by developing earlier maturing cotton cultivars which evaded some damage from boll weevil, yet still allowed a crop to be produced, albeit less profitable. Following World War II, organic insecticides were developed which were very effective in controlling cotton pests, especially the boll weevil. Consequently, breeders began to develop cotton cultivars which again used a longer part of the potential growing season. These longer-season cotton cultivars produced more lint and were more profitable than the short-season cultivars. Reviews of the progress and problems associated with boll weevil control have been presented by Adkisson *et al.* (1982), Frisbie and Walker (1981), Parker *et al.* (1980), Walker (1980a,b), Walker (1984), Walker *et al.* (1978) and Walker *et al.* (1984).

Beginning about 1960 several states and the United States Department of Agriculture, Agricultural Research Service began extensive research programs aimed at identifying characteristics in cotton which were useful in the development of cultivars with increased levels of resistance to several insect pests. Reviews have been written by Jenkins (1982a,b), Maxwell *et al.* (1972), Niles (1980) and Wilson (1982).

This chapter will not attempt to exhaustively survey and report the literature on host plant resistance in cotton, but will attempt to document the present state of the art in this area of science.

GERMPLASM SOURCES OF PEST RESISTANCE

CULTIVATED COTTONS

Earliness — In the Mid-South, a cotton plant initiates about 60 flower buds (squares) over a 12-week period and eventually matures 10-15 bolls per plant. An average stand of 30,000 plants per acre equates to 1.8 million squares and 290,000 to 445,000 [=10-15 bolls/plant] mature bolls. This number of bolls would represent an estimated lint yield of 2.4 to 3.6 bales per acre. This estimate represents an effective fruit set and harvest, yet it is only 15-25 percent of the squares initiated by the plant. The number of fruit initiated, and the time and rate of their initiation and maturation have direct relationships to insect pests and the damage that they cause.

When plants harbor lower pest populations because they are early maturing this is considered host evasion rather than true resistance (Painter, 1951). Nevertheless, earliness is a very important component in insect control, as already stated in the case of the boll weevil. Because of the nature of the fruiting cycle in cotton, breeders can exert a great amount of control over the plant. After many years of developing full-season cultivars and depending heavily upon insecticides, breeders once again are developing early-season cultivars and growers are using these in systems to produce cotton at a profit. Researchers and producers in Texas were among the first to utilize these systems to advantage. Theoretical and applied approaches were developed by Adkisson *et al.* (1982), El-Zik and Frisbie (1985), Frisbie (1981), Namken *et al.* (1983) and Walker and Niles (1980).

Even in other areas of the United States, cotton cultivars grown in 1987 were far different from those grown in most states in 1972. In 1972, two cultivars, 'Stoneville 213' and 'Deltapine 16' accounted for 50 percent of the United States acreage; however, by 1986 it required six Stoneville and 13 Deltapine cultivars to account for 43 percent of the United States acreage (Bridge and McDonald, 1987). In 1986 the five most popular cultivars accounted for only 37 percent of the United States acreage. Thus, the cultivars being grown by United States growers are changing rapidly (Bridge and McDonald, 1987). These changes are in the direction of earlier maturing cultivars which bear directly on the pest problems in the crop. Earlier maturing cultivars are in many instances more resistant to pests. This resistance involves escape or pest evasion as well as direct forms of resistance. Early cultivars thus produce a crop which receives less damage from insect pests than those grown in prior years. This is effective host plant resistance in practice.

Bridge and McDonald (1987) present data which show a decrease in number of days from planting to harvest of 32 days (last 28 years) at Stoneville, Mississippi; 45 days (last 20 years) at Sumner, Mississippi; 28 days (last 21 years) at College Station, Texas; and 33 days (last 19 years) at Florence, South Carolina. These are dramatic increases in earliness. Yields have also increased during this time.

The major shifts in cultivars began in Texas in the early 1970s and in the late 1970s in the Mid-South. These shifts were associated with the release of the Tamcot (Bird, 1976; Bird *et al.*, 1986) cultivars in Texas and the release of 'Stoneville 825' in 1978 followed by 'DES 56', 'DES 422', 'DES 119', 'Stoneville 603', 'Deltapine 41', 'Deltapine 50' and 'Deltapine 20' in Mississippi. In 1978, the Rio Grande Valley area of Texas was growing 25 percent early-maturing cultivars whereas the Corpus Christi area was growing 82 percent early-maturing cultivars. By 1986 these figures were 98 and 100 percent. The Mid-South area had 8-25 percent in early maturing cultivars in 1976 and 78-99 percent (depending upon the state) in 1986. The shift to earlier maturing cultivars is just beginning in the irrigated desert areas of southern California (Kerby *et al.*, 1988, 1990). Also, a shift could occur in the San Joaquin Valley of California, where considerable research has been done on short-season strains (Burch, 1988).

Morphological Traits — There are a number of plant traits which affect insect pests of cotton (Table 1). With many there are trade offs, as they confer resistance to one insect while increasing susceptibility to one or more others.

The Stoneville 825 cultivar is nectariless (i.e., lacks extrafloral nectaries, but has floral nectaries). It has been grown on large acreage. Nectariless improves resistance to the bollworm, *Helicoverpa zea* (Boddie), and tobacco budworm, *Heliothis virescens* (F.); less eggs are deposited on nectariless cotton (Meredith, 1990). It also confers resistance to plant bugs by causing reduced oviposition and the nectar food source for nymphs (Schuster *et al.*, 1976; Parrott *et al.*, 1982). It confers resistance to pink bollworm, *Pectinophora gossypiella* (Saunders), particularly in conjunction with the okra leaf trait (Wilson, 1987). Nectariless also confers resistance to the cotton leafperforator, *Bucculatrix thurberiella* Busck., (Henneberry *et al.*, 1977). Nectariless also affects the food source for predators that feed on nectar and, thus their numbers are decreased. No major adverse agronomic or fiber properties have been found to be associated with nectariless (McCarty *et al.*, 1983; Meredith and Bridge, 1977).

Pilose plants are densely pubescent (hairy). This pubescence increases resistance to plant bugs and boll weevil, but oviposition (laying of eggs) by bollworm/tobacco budworm moths and whiteflies increases. Pubescence is associated with resistance to thrips in the seedling stage.

Pilose is a gene with detrimental effects on agronomic properties and yield. However, there are other pubescence genes that do not have this effect. Pilose and the other pubes-

Table 1. Morphological traits of cotton and their effects on pest resistance and agronomic traits.

	Leaf-hoppers	Boll weevil	Bollworm/ Tobacco budworm	Plant bugs	Bandedwinged whitefly	Cotton leafperforator	Pink bollworm	Thrips	Agronomic traits
Glabrous	S		R	S	R	R		S	N
Pilose	R	R	S	S	S	R	R	R	D
Okra-leaf		R		S	R		R		N
Frego		R	R	S					N
Red plant		R				S	S		D
Yellow pollen			R						N
Orange pollen			R						N
Nectariless			R	R		R	R		N
High gossypol			R	R			R		N
Male sterile			R						
Cytoplasms									
barbadense			R						N
tomentosum			R						N
arboreum		R							D
herbaceum		R							D
anomaleum		R							D
harknesii		R							D

R indicates the trait increases resistance to this pest.
S indicates the trait increases susceptibility to this pest.
N indicates the trait has a neutral effect on yield and agronomics.
D indicates the trait has a decreasing effect on yield and agronomics

cent traits increase the trash content of mechanically harvested cotton; thus, it is not likely to be used in the United States.

As stated earlier, pubescent cottons were the first trait used in Africa for leafhopper control and were very effective for that purpose. Lack of plant pubescence (glabrousness or smoothleaf) reduces bollworm/tobacco budworm oviposition and numbers of whiteflies and cotton leafperforator. On the other hand, glabrous cottons are susceptible to plant bugs, thrips and *Empoasca* spp., jassids (leafhoppers).

The okra-leaf trait increases the earliness of cotton strains and is thus useful in boll weevil control. It also changes the microclimate and allows more desiccation by high temperatures to squares with immature boll weevil larvae. It has also shown resistance to bandedwinged whitefly, *Trialeurodes abutilonea* (Haldeman) (Jones *et al.*, 1975). It is useful for pink bollworm control.

Three strains which possess both the nectariless and okra-leaf traits have been released. They are more resistant to pink bollworm than currently grown commercial cultivars (Wilson, 1987).

High yielding cultivars with the okra-leaf trait have been developed for use in Louisiana (Burris *et al.*, 1981). The okra-leaf trait also reduces boll rot due to the more open canopy (Andries *et al.*, 1970). A cultivar of okra-leaf cotton (SIOKRA) grown in Australia improved cotton pest management (Personal communication, Brian Hearne and Norm Thompson, CSIRO Division of Plant Industry, Cotton Research Unit, New South Wales Agricultural Research Station, Australia) and produced high yields (Reid *et al.*, 1989). Okra leaf increases penetration of insecticidal sprays into the plant canopy. It seems to be more sensitive to environmental stress than normal-leaf cultivars and will suffer yield reductions under adverse growing conditions (Landivar *et al.*, 1983a,b; Meredith and Wells, 1987).

Frego bract increases resistance to boll weevil, and in some breeding lines, to bollworm/tobacco budworm while increasing susceptibility to plant bugs. Frego bract allows better penetration of insecticide and decreases boll rot because the bracts do not enclose the boll. High yielding lines have been developed that combine frego bract with the nectariless and rapid fruiting traits. These lines are competitive in yield with normal bract cultivars. Their usefulness in boll weevil control is discussed under the section on boll weevil in this chapter.

Red-pigmented plants are apparently more difficult for the boll weevil to locate. Once weevils are on red cotton, however, it is as susceptible as green cotton (Hunter *et al.*, 1965; Isley, 1928). Red plants are more susceptible than green plants to pink bollworm and to cotton leafperforator. Red has a slightly negative effect on yield of cotton (Jones and Brand, 1981). It has been used successfully in trap crop situations in Louisiana and in Georgia for boll weevil control where the major part of the field is planted in red cotton and the trap rows in green (Weaver and Reddy, 1977). It is not as useful for this purpose as is frego bract, nor is it as effective as using adapted cultivars for the major part of the field and using early, highly susceptible, strains for the trap rows (Jones *et al.*, 1987a).

Yellow or orange pollen mutants show antibiosis to tobacco budworm when compared with the predominant cream pollen cultivars. No serious effort to use these in the development of cultivars has been reported. However, since most upland cultivars have cream pollen, this result may indicate that other pollen colors have a detrimental effect on yield.

Biochemical Mutants — High levels of gossypol and other allelochemicals have been shown to be antibiotic to bollworm/tobacco budworm larvae. Much research has been directed towards using high gossypol as a source of resistance to the bollworm and tobacco budworm, but this trait has shown resistance to other insects as well. In 1988, high yielding cotton germplasm with high levels of gossypol were registered with the Crop Science Society of America (Jones *et al.*, 1988b). The usefulness of this trait and some of its possible problems are discussed under the section on bollworm/tobacco budworm. At this stage of the development of resistant cultivars, it appears that high levels of gossypol can be used without a detrimental effect on agronomic properties and yield.

Exotic Cytoplasms — Cytoplasms from two tetraploid and four diploid cottons have been evaluated for resistance to pests (Table 1). The diploid cytoplasms result in less oviposition by the boll weevil (McCarty, 1974; McCarty *et al.*, 1977). These diploid cytoplasms however, generally have a detrimental effect on yield (Meredith *et al.*, 1979b). *Gossypium tomentosum* (Nuttall) cytoplasm is antibiotic to bollworm/tobacco budworm larvae and results in about a 15 percent reduction in larval size (Jenkins *et al.*, 1986; Meredith *et al.*, 1979b).

Germplasm releases — Several *Gossypium hirsutum* germplasms with single or combinations of resistance traits (glabrous, nectariless, frego bract, okra leaf, high gossypol) have been developed and registered (Table 2). Three of these are useful for control of pink bollworm (Wilson, 1987). These germplasms are in several cultivar backgrounds and generally have yields similar to the recurrent cultivar parent (Lee, 1977; Meredith and Bridge, 1977; Shepherd, 1982 a,b,c,d; Shepherd and Kappelman, 1982a; Shepherd *et al.*, 1986a,b; and Wilson, 1987). The nectariless and okra-leaf traits are also being transferred into Pima (*Gossypium barbadense*) background (Personal communication, R. Percy, Western Cotton Research Laboratory, United States Department of Agriculture, Agricultural Research Service, Phoenix, Arizona).

PRIMITIVE RACE COLLECTION

Breeding for resistance to pests requires a reservoir of genes for resistance. A good source of genes is the collection of primitive cottons. A number of these have been evaluated for pest resistance (Table 3). Most reports of evaluations do not include breeding lines which are not resistant. Thus, the data reported in Table 3 show resistance for each pest where it has been reported. However, the lack of a resistance indication does not mean that the line is susceptible; it may not have been evaluated for the particular pest.

Multiple pest resistance is common in the race collection. There are 228 lines resistant to one or more pests. There are 33 lines high in gossypol which should confer resistance to the bollworm/tobacco budworm complex. There are 56 lines which have been identified as resistant to bollworm/tobacco budworm. There are 59 lines resistant to boll weevil, 99 resistant to pink bollworm, six resistant to mites, and 11 resistant to plant bugs. These lines and this collection are valuable resources for future work on resistance to pests of cotton. The evaluations which provided data for these counts or resistant lines show that much useful variability is available in this collection. Its use will require long-term breeding goals since much of the collection is photoperiodic and will not flower in the long days of the United States Cotton Belt in the summer. Conversion programs are underway in the authors' USDA, ARS laboratories in Mississippi and Arizona to breed day-neutral genes into the *Gossypium hirsutum* and *Gossypium barbadense* lines, respectively, in this collection. This is also a long-term program; however, each year a group of lines is released to the public from this research program (McCarty *et al.*, 1979).

Table 2. Registered germplasm of cotton with morphological or biochemical mutants conferring resistance to one or more pests[1].

Registration No.	Strain	Originator	Year Registered
36-37	2 smoothleaf strains	Lee	1977
27-35	9 nectariless (NE) strains	Meredith & Bridge	1977
167-174	8 frego strains	Shepherd	1982
175-182	8 nectariless strains	Shepherd	1982
183-185	3 okra-leaf, frego bract strains	Kappelman	1982
186-193	8 okra-leaf strains	Shepherd	1982
194-201	8 smoothleaf strains	Shepherd	1982
270-277	8 okra-leaf, frego bract strains	Shepherd *et al.*	1986a
278-285	8 nectariless, frego bract strains	Shepherd *et al.*	1986b
260,263, 264,266	4 nectariless, okra-leaf strains	Wilson	1986
305,307	2 nectariless, okra-leaf strains	Wilson	1987
306	1 nectariless, okra-leaf, smooth strain	Wilson	1987
313-315	3 high gossypol strains	Jones *et al.*	1988b

[1]Registered with the Crop Science Society of America, 677 South Segoe Rd., Madison, Wisconsin 53711.

Table 3. Accessions in upland cotton, *Gossypium hirsutum* race collection with pest resistance.

Accessions with high gossypol: 102, 114, 115, 144, 152, 165, 187, 197, 216, 231, 258, 277, 297, 306, 345, 487, 490, 495, 497, 499, 606, 642, 663, 664, 665, 674, 707, 766, 805, 934, 952, 1036, 1150

Boll weevil resistant race accessions: 11, 18, 26, 78, 80, 94, 109, 118, 128, 140, 147, 185, 192, 196, 209, 260, 265, 267, 292, 293, 294, 295, 297, 304, 323, 326, 330, 333, 336, 339, 340, 347, 461, 600, 625, 679, 681, 720, 725, 730, 732, 756, 759, 760, 763, 764, 771, 786, 790, 805, 938, 952, 955, 1067, 1105, 1119, 1134, 1149, 1150

Bollworm/tobacco budworm resistant race accessions: 16, 72, 91, 100, 102, 104, 110, 113, 119, 130, 163, 164, 165, 167, 171, 187, 195, 201, 206, 219, 228, 247, 254, 295, 490, 600, 620, 670, 675, 681, 682, 687, 693, 697, 707, 709, 766, 776, 802, 805, 953, 999, 1001, 1006, 1015, 1036, 1040, 1041, 1066, 1067, 1102, 1106, 1108, 1121, 1132, 1150

Pink bollworm resistant race accessions: 7, 17, 20, 21, 25, 31, 39, 40, 41, 53, 55, 58, 62, 65, 72, 78, 93, 99, 101, 102, 103, 127, 142, 158, 160, 164, 167, 168, 169, 170, 175, 176, 180, 181, 185, 202, 203, 207, 216, 218, 220, 226, 228, 232, 245, 247, 254, 257, 265, 273, 293, 302, 303, 306, 316, 330, 331, 333, 335, 336, 339, 342, 377, 389, 469, 489, 497, 503, 570, 596, 610, 616, 620, 635, 636, 639, 646, 657, 658, 668, 679, 682, 703, 705, 711, 712, 763, 764, 775, 937, 955, 960, 1048, 1053, 1125, 1158, 1177, 1180, 1182

Spider mite resistant race accessions: 1, 5, 110, 118, 144, 165

Plant bug resistant race accessions: 78, 113, 158, 195, 247, 254, 481, 655, 658, 682, 701

RESISTANCE TO INSECTS AND MITES

BOLL WEEVIL

The boll weevil is a major pest in much of the Cotton Belt. It has been eradicated in North Carolina and South Carolina; eradication projects are proceeding in Florida, Georgia, and parts of Alabama, Arizona, and California. Planning is underway to eradicate it in other states.

The correct management of the boll weevil supports effective pest management programs for other cotton insects. The use of resistant cultivars, i.e., early season cultivars having a useful level of resistance as well as pest evasion, coupled with recommended management practices, has relegated the boll weevil to a manageable status in much of Texas (Adkisson *et al.*, 1982; El-Zik and Frisbie, 1985; Frisbie, 1981; Namken *et al.*, 1983; Parker *et al.*, 1980; Walker, 1980a,b; Walker *et al.*, 1978; Walker, 1984; Walker *et al.*, 1984).

Because of these events, most seed breeding firms are not actively pursuing programs to develop cultivars with specific resistance to boll weevil, but they are developing early, short-season cultivars which aid in its management. These cottons first became available as cultivars in Texas in the mid-1970s and in the Mid-South in the early-1980s. Growers have several cultivars to choose from in each region. Table 4 lists those which have been officially registered with the Crop Science Society of America.

Many cultivars developed by private seed companies are never registered with the Crop Science Society of America (Table 5). Many germplasm resources are available to use in developing cultivars with resistance to boll weevil (Table 6). The most prevalent type of resistance is a reduction in oviposition (Buford *et al.*, 1967; Buford *et al.*, 1968; Jenkins *et al.*, 1964; Jenkins *et al.*, 1969; Jenkins *et al.*, 1978; Lambert *et al.*, 1980; McCarty and McGovern, 1987; McCarty and Jones, 1988; McCarty *et al.*, 1986b; McCarty *et al.*, 1977; McCarty *et al.*, 1982a; Weaver and Reddy, 1977). Several cases of antibiosis have also been reported (Bailey *et al.*, 1967; Black and Leigh, 1963; Hunter *et al.*, 1965; Jenkins *et al.*, 1964). The very pubescent cottons are less preferred by the boll weevil (Hunter *et al.*, 1965; Wannamaker *et al.*, 1957).

Over 60 accessions in the collection of wild races of cotton are resistant to the boll weevil. Resistance is expressed as reduced oviposition (Jenkins *et al.*, 1978). These race stocks are generally photoperiodic, but some have been developed into day-neutral lines and still retain the resistance to boll weevil (Table 5). MWR-1 and MWR-2, boll weevil resistant lines, have been released to the public and registered with the Crop Science Society of America (McCarty et al., 1986b). Day-neutral lines from *Gosspium hirsutum* race accessions 80, 759, 1149, 109, 293, 326, 330, 763 and 1180 are resistant to the boll weevil in the field (Jones *et al.*, 1987a; McCarty and Jones, 1989; McCarty *et al.*, 1982a). A listing of the race lines resistant to boll weevil and their known cross resistance to other pests are shown in Table 3.

Host plant resistance research with the boll weevil has led to the discovery of numerous substances in cotton that act as feeding deterrents, feeding stimulants, attractants or arrestants for the boll weevil (Benedict *et al.*, 1987; Hedin *et al.*, 1974; Hedin

Table 4. Registered cultivars and germplasm of cotton which are early, short season types[1].

Registration No.	Cotton line	Type	Originator	Year registered
61	Tamcot SP21	Cultivar	Bird	1976
62	Tamcot SP23	Cultivar	Bird	1976
63	Tamcot SP37	Cultivar	Bird	1976
69	DES24	Cultivar	Bridge & Chism	1978a
70	DES56	Cultivar	Bridge & Chism	1978b
74	Tamcot CAMD-E	Cultivar	Bird	1979
73	Tamcot SP21S	Cultivar	Bird	1976
75	Tamcot SP37H	Cultivar	Bird	1979
156	DES-04-6	Germplasm	Bridge	1980
157	DES-04-11	Germplasm	Bridge	1980
158	DES-04-606	Germplasm	Bridge	1980
163	HYC 76-59	Germplasm	Sappenfield	1981
225	UARK-1	Germplasm	Smith	1983
226	UARK-2	Germplasm	Smith	1983
86	PD-2	Germplasm	Culp *et al.*	1985
88	DES-119	Cultivar	Bridge	1986b
87	Tamcot CABCS	Cultivar	Bird *et al.*	1986
303	Miscot 7813	Germplasm	Bourland	1987
304	Miscot 7841	Germplasm	Bourland	1987
308	DES 237-7	Germplasm	Bridge	1987
92	Arkot 518	Cultivar	Smith	1988
94	Tamcot CD3H	Cultivar	Bird *et al.*	1988
319-332	CS-8601 to CS-8614	Germplasm	Smith & Niles	1988
316	Miscot 7913-51	Germplasm	Bourland	1988
317	Miscot 7913-83	Germplasm	Bourland	1988
318	Miscot 7913-84	Germplasm	Bourland	1988

[1]Registered with the Crop Science Society of America, 677 South Segoe Rd., Madison, Wisconsin 53711.

Table 5. Cultivars (varieties) of cotton developed by private seed companies for short-season production.

Cultivar	Developer
Stoneville 506	Stoneville Pedigreed Seed Company
Stoneville 112	Stoneville Pedigreed Seed Company
Stoneville 132	Stoneville Pedigreed Seed Company
Stoneville 453	Stoneville Pedigreed Seed Company
Stoneville 825	Stoneville Pedigreed Seed Company
Deltapine 20	Deltapine Seed Company
Deltapine 50	Deltapine Seed Company
Deltapine 41	Deltapine Seed Company
Coker 208	Coker Pedigreed Seed Company
Coker 304	Coker Pedigreed Seed Company
Coker 235	Coker Pedigreed Seed Company
Centennial	Sun Valley Seed Company
White Lightning	Seeds of Tomorrow
Short Cut	Seeds of Tomorrow

et al., 1977; Jenkins *et al.,* 1963; Keller *et al.,* 1962; Keller *et al.,* 1963; Maxwell *et al.,* 1963a, b; Maxwell *et al.,* 1965; McKibben *et al.,* 1985). Some of these have found practical use as adjuncts to baits or pheromones such as the commercial product NoMate Blockade® and the Boll Weevil Bait Stick (McKibben and Smith, 1991).

The frego bract character effectively can reduce the population of boll weevils; thus, it is an effective trait to use in developing cultivars resistant to the boll weevil (Jenkins, 1982ab; Jenkins and Parrott, 1971; Jenkins *et al.,* 1969; Jones *et al.,* 1983; McCarty *et al.,* 1983). Boll weevil oviposition (egg laying) in plots of frego-bract cotton was suppressed 66, 71, 75 and 94 percent below oviposition in non-frego cotton plots in field studies with this trait (Jenkins and Parrott, 1971). A problem with the use of frego bract is its sensitivity to plant bugs. Addition of the nectariless trait helps in this regard as does breeding frego bract into early maturing cultivars (Jones *et al.,* 1983; Milam *et al.,* 1982).

The trap crop principle using lines which vary in their preference by the boll weevil has been demonstrated in Louisiana (Burris *et al.,* 1982); Jones and Brand, 1981; and Jones *et al.,* 1987 a,b). The cottons Tamcot CAB-CS, TX CAMD 21S-7-81 and TX BLLEBOS 1-83 are more attractive to boll weevil than 'Deltapine 41'; they also fruit earlier. Therefore, they are especially useful in the trap crop system for boll weevil control (Jones *et al.,* 1987a).

Table 6. Summary of evaluations for resistance to boll weevil in cotton.

Resistant source and type	Reference
Antibiosis	
Gossypium arboreum, Gossypium davidsoni, Gossypium thurberi	Bailey *et al.*, 1967
Gossypium thurberi, Pima S-1	Jenkins *et al.*, 1964
Gossypium barbadense	Black & Leigh 1963
Hopi Russian 5A, CB2545	Hunter *et al.*, 1965
Reduced oviposition	
Triple Hallmark SI, Seaberry SI, Russian SI, Brown Egyptian	Buford *et al.*, 1967, 1968
5 frego, 4 red, SI Seaberry	Jenkins *et al.*, 1969
MWR-1, MWR-2	McCarty *et al.*, 1986b
Male sterility	Weaver *et al.*, 1977
Lansii 11, AC134, Albar 627, G077-2, BPA52/NC63, Tx-Ly-18-72 gl, DES-HERB-16, DES-ARB-16	Lambert *et al.*, 1980
75 *Gossypium hirsutum* race lines	McCarty *et al.*, 1977, 1982a
	McCarty, 1987
	Jenkins *et al.*, 1978
Nonpreference	
Hairy plants	Hunter *et al.*, 1965
MU-9, Pilose, R1	Wannamaker, 1957

BOLLWORM/TOBACCO BUDWORM COMPLEX

Much effort is directed towards control of these two species of cotton. Many of the presently recommended control practices depend upon using early, short-season cultivars as a foundation for pest management. This approach is used very effectively in Texas (Adkisson *et al.*, 1982; El-Zik and Frisbie, 1985; Frisbie and Walker, 1981; and Walker *et al.*, 1978).

Considerable effort has been directed toward understanding the relationship between cotton and the bollworm/tobacco budworm complex. These pests feed on several host plant species and usually feed on a succession of hosts during the year. Control of bollworm/tobacco budworm on host plants other than cotton has the potential to solve their pest status on cotton. In the Mid-South, tobacco budworms oviposit most of their eggs in the upper one-third of the plant, usually near the terminal, except during the late part of the season (Ramalho *et al.*, 1984). First and second instar tobacco budworm larvae are generally found in the upper one-third of the plant canopy except late in the season. Instars three through six are found moving throughout the plant canopy. All larval instars are found primarily on structures that arise from the first position on a branch (Ramalho *et al.,* 1984). In field studies on the bollworm, site of oviposition had little effect on the level of establishment; however, in laboratory studies larval development was affected by feeding site with larvae on flowers and bolls developing faster and growing larger than those on squares, leaves and terminals (Farrar *et al.,* 1985). First instar larvae of tobacco budworm avoid feeding on gossypol glands (Parrott *et al.,* 1983).

Cotton contains many chemicals which retard the growth of bollworm/tobacco budworm larvae. Numerous laboratory studies have shown that these are effective (Bell and Stipanovic, 1977; Bell *et al.,* 1974; Chan and Waiss, 1981; Chan *et al.,* 1978a,b,c; Elliger *et al.,* 1978; Jenkins *et al.,* 1983; Lukefahr and Martin, 1966; Lukefahr and Houghtaling, 1969; Waiss *et al.,* 1981). Numerous cotton lines have been developed or evaluated with various levels of one or more of these chemicals which reduce the growth of larvae (Table 7). Yellow or orange pollen reduces the growth of larvae (Bailey, 1981; Hanney *et al.,* 1979). Nectariless strains of cotton reduce oviposition of moths as do glabrous leaves (Lukefahr *et al.,* 1971; Lukefahr *et al.,* 1975).

In the collection of wild cottons, over 60 lines show antibiosis toward larvae of tobacco budworm or bollworm (Parrott *et al.,* 1978; Personal communication, J. E. Jones, Louisiana State University, Baton Rouge, Louisiana) (Tables 3 & 7). Additionally, 32 lines from the collection are high in gosspol (Dilday and Shaver, 1976a,b; Dilday and Shaver, 1980) (Table 7). Nine of the high gosspol accessions show antibiosis (antagonistic association) against bollworm/tobacco budworm. The remaining high gossypol lines also should be resistant.

A diverse group of cottons were grown in Mississippi and tobacco budworm larvae were grown from emergence to five days of age on the different cotton lines. Concurrently, the lines were sampled and analyzed for certain classes of chemicals alleged to be antibiotic to the larvae. Tannin level was not related to larval growth. Negative relationships were shown between level of gossypol and larval growth, and level of a mixture of flavonoids and anthocyanin and growth (Jenkins 1982b; Jenkins *et al.,* 1983; White, 1981; White *et al.,* 1982a,b).

Many cotton constituents are antiobic to tobacco budworm larvae when added to diets. The amount of chemical necessary to reduce growth 50 percent varies from 0.03 to 0.46 percent of the diet (Bell and Stipanovic, 1977; Bell *et al.,* 1974; Chan and Waiss, 1981; Chan *et al.,* 1978a,b; Jenkins *et al.,* 1983; Waiss *et al.,* 1981) (Table 8).

Larvae grow much faster on artificial diet than on cotton plants, presumably because of the number and amount of allelochemicals[1] in the plant and the better nutrition available in the artificial diet. At the end of day one, larvae on diet are two times larger than those on cotton. At the end of five days those on cotton weigh 2.5 milligrams, whereas, those on diet weigh 20 milligrams. At day 9, those on cotton weigh 60 milligrams and those on diet weigh 300 milligrams (Jenkins, unpublished data). The small larvae, however, are quite capable of damaging cotton.

[1]Allelochemicals are naturally occurring behavior-modifying chemicals that mediate interspecific interactions. See Chapter 11 for more information on such chemicals.

Table 7. Summary of evaluations for resistance to bollworm/tobacco budworm in cotton.

Resistant source	Reference
Antibiosis	
High gossypol	Lukefahr & Houghtaling, 1969
	Lukefahr *et al.*, 1975
Gossypium tomentosum cytoplasm	Meredith *et al.*, 1979b
Yellow pollen	Hanney *et al.*, 1979
Orange pollen	Bailey *et al.*, 1984
BJA592, Laxmi, Satu-65, MOHG, HGBR-8N	Lambert *et al.*, 1982a
Gossypol, quercetin, rutin	Lukefahr & Martin, 1966
BW76-31	Stokes & Sappenfield, 1981
Heliocides H1 & H2, Hemigossypolone	Elliger *et al.*, 1978
Catechin, chrysanthemin, isoquercetrin, delphinidin, quercetin, condensed tannins, cyanidin gossypol	Jenkins *et al.*, 1983
T-934 Socorro Island Wild	Dilday & Shaver, 1980
Race accessions 91, 122, 113, 100, 104, 195, 228, 201, 102, 110, 171, 119	Parrott et al., 1978
48 *Gossypium hirsutum* race accessions	Jones, Personal Communication[1]
Red plant color	Bhardwaj & Weaver, 1983
Gossypium arboreum, Gossypium bickii, Gossypium herbaceum, Gossypium somalense	Benedict *et al.*, 1987
Reduced Oviposition	
Smoothleaf	Lukefahr *et al.*, 1971
Nectariless	Lukefahr *et al.*, 1975
NC-1, NC-2	Lee, 1977
Ability to yield under infestation	
CAMD-E, PD 875, PD 8619, ST-506	Jenkins *et al.*, 1986
High gossypol	
33 *Gossypium hirsutum* race accessions	Dilday & Shaver, 1976a,b
	Dilday & Shaver, 1980

[1]J. E. Jones, Professor of Agronomy, Louisiana State University, Baton Rouge, Louisiana 70893.

Table 8. Percent allelochemical required in laboratory diet to reduce bollworm/tobacco budworm larval growth 50 percent.

	Evaluated by		
Allelochemical	Chan	Stipanovic	Missississippi State University
Gossypol	0.12	0.05	0.12
Hemigossypolone	0.03	0.29	—
H1	0.12	0.10	—
H2	0.13	0.46	—
Catechin	0.13	—	0.05
Epicatechin	—	—	0.11
Quercetin	0.05		0.05
Condensed tannin	0.15		0.05
Methyl sterculate	0.41		—
Cyanidin	—		0.15
Delphinidin	—		0.13
Flavonoids & anthocyanin mixture (F7)	—		0.07

Table 9. Regression equation for allelochemical effects on first instar tobacco budworm larvae grown on diet for 5 days.

Allelochemical	Regression form	a	b	Coefficient of determination r^2	Significance of Regression	r
Catechin	$Y=aX^b$[1]	7.06	-0.562	0.90	**	**
Chrysanthemin	$Y=aX^b$	7.911	-0.707	0.81	**	**
Isoquercitrin	$Y=aX^b$	4.49	-0.888	0.85	**	**
Quercetin	$Y=aX^b$	3.29	-0.705	0.90	**	**
Condensed tannin	$Y=aX^b$	2.07	-0.880	0.90	**	**
Cyanidin	Y=a+bX	105.10	-332.9	0.71	**	**
Delphinidin	Y=a+bX	124.40	-540.4	0.89	**	**
Gossypol	Y=a+bX	101.61	-390.3	0.56	**	**

**Significant at 0.01 level.

[1] $Y = aX^b$ is same as $\log Y = \log a + b \log X$.

From: Jenkins *et al.*, 1983.

Regression equations for larval growth as a function of level of allelochemical in artificial diet indicated a linear relationship for the chemicals cyanidin, delphinidin and gossypol. Curvilinear relationships were found for catechin, chrysanthemin, isoquercitrin, quercetin and condensed tannin (Table 9) (Jenkins *et al.*, 1983). Using these relationships to calculate the level of allelochemicals necessary to reduce growth of larvae 90 and 95 percent, 0.235 and 0.248 percent gossypol are required, respectively. For isoquercitrin, a curvilinear relationship exists and 0.538 and 1.848 percent are required for a 90 and 95 percent reduction in growth (Table 10) (Jenkins *et al.*, 1983). These levels are within the limits of those found naturally in cotton plants.

Increasing the natural level of allelochemicals in cotton has been the goal of several research programs. In this context, the interaction of cotton genotype and environment and the type of gene action involved in allelo-chemical production are both important. Fortunately, these are within ranges which allow their use by cotton breeders.

Six types of chemical analyses were performed on a group of cotton lines (strains) from which samples were collected weekly. Data for selected weeks are shown in Table 11 (White *et al.*, 1982b). Each of the chemicals varied over the season whether considered from individual strains (lines) or as means over all strains. Components of variance analyses for the chemicals showed that weeks (i.e., stage of growth) was a much larger component than strains; however, significant variability was evident among the strains and there was not a large strains by week interaction. This indicates that in each cotton strain the level of the allelochemical varied across weeks, but it varied in a similar manner in each of the cotton strains in the experiment. Broadsense heritability estimates were 93 to 99 percent (Table 12) (White *et al.*, 1982a).

Genetic studies on three cotton crosses produced estimates of the various types of gene action. For each chemical, except aniline reacting terpenes, additive effects were the largest component. Dominance effects were important for phenolics as well as aniline reacting terpines (Table 13) (White, 1981; White *et al.*, 1982b). Thus, breeders can select for higher levels of these chemicals and expect to be successful. Samples for comparison purposes should be collected at the same time because of the week-to-week variation; however, genetic effects should not be confounded by a major genotype by environment interaction (Dilday and Shaver, 1980; White *et al.*, 1982b).

Plant breeders have actively cooperated with entomologists for several years to identify strains of cotton with antibiosis against the bollworm/tobacco budworm. Numerous obsolete cultivars, wild race accessions and special genetic stocks have been identified (Table 7). Techniques are now available which allow the breeder to select resistant plants from segregating progeny or progeny rows following crosses between resistant and susceptible lines. Most of the resistant lines were found originally in nonadapted cottons. Techniques have been developed for infesting plots with eggs; however, these were not considered to be as useful as those using first instar larvae. The technique of choice distributes first instar larvae mixed with corncob grits onto terminal leaves (Hall *et al.*, 1980; Jenkins *et al.*, 1982). Larval rearing and field distribution procedures have been developed for achieving uniform infestations (Jenkins *et al.*, 1982; Parrott *et al.*, 1986). These techniques are useful in their present

Table 10. Predicted amounts of allelochemicals necessary in diet to achieve desired level of growth reduction in tobacco budworm, based upon regression equations. (From Jenkins *et al.*, 1983.)

	Desired percent of weight on control diet								
Allelochemical	100	75	50	25	10	5	2	1	0
	% allelochemical								
Catechin	0.009	0.015	0.131	0.105	0.538	1.848	9.430	32.360	—
Chrysanthemin	0.028	0.042	0.074	0.196	0.727	1.913	6.988	18.620	—
Isoquercitrin	0.030	0.042	0.066	0.145	0.406	0.886	2.485	5.425	—
Quercetin	0.008	0.012	0.021	0.056	0.207	0.552	2.025	5.412	—
Condensed tannin	0.012	0.017	0.027	0.059	0.167	0.367	1.041	2.285	—
Cyanidin	0.015	0.090	0.166	0.241	0.286	0.301	0.310	0.313	0.316
Dephinidin	0.045	0.091	0.138	0.184	0.212	0.221	0.227	0.228	0.230
Gossypol	0.004	0.068	0.132	0.196	0.235	0.248	0.255	0.258	0.260

Table 11. Allelochemical concentration in cotton terminal leaves over time. Mean of 20 strains. (From White *et al.*, 1982b.)

Compound	Sampling dates (week postemergence)					Season
	5	7	9	11	13	mean
	Percent dry weight basis					
Tannin	5.8	13.0	18.1	17.5	21.3	16.1
E1, 1	5.9	10.2	13.8	13.9	16.2	12.6
Catechin	6.7	11.9	14.5	12.4	13.9	12.6
Phenolics	4.7	5.5	7.6	11.6	19.7	10.2
Gossypol	0.28	0.38	0.28	0.24	0.20	0.27
Flavonoids & anthocyanin	0.38	0.63	0.48	0.45	0.36	0.45

Table 12. Estimates of components of variance for cotton allelochemicals from a group of 20 cotton strains sampled for 10 weeks. (From White *et al.*, 1982a.)

Compound	Mean squares[1]			Broad sense
	Strains	Week	SxW	heritability
Tannin	930**	3004**	171**	97.7
E1, 1	4**	10**	1**	97.5
Catechin	222**	834**	25**	98.3
Phenolics	18	3029**	0	93.2
Gossypol	1.5**	0.3**	0	99.2
Flavonoids & anthocyanin	8**	1**	1**	98.9

[1] ** significant F value at 0.01 level.

Table 13. Mean squares from Generation Mean Analysis from three sets of crosses illustrating genetic effects involved in allelochemicals in cotton. (From White *et al.*, 1982a.)

	Genetic effects for crosses								
	Set 1			Set 2			Set 3		
Allelochemical	A	D	RE	A	D	RE	A	D	RE
	milligram/gram dry weight								
E1,1 tannin	.0046*			.0032*					
Catechin				18739*					
Total phenolics							210.0*	93.0*	
Aniline reacting terpines		27.7*	9.0*		29.9*	17.7*			
Gossypol	10.0*						4.2*		1.8*
Flavonoid/ anthocyanidin	10.1*			6.5*					

A = Additive effects.
D = Dominance effects.
RE = Residual epistatic effects.
* = Significant effect at 0.05 level of significance.

form to commercial plant breeding firms. One company is presently using these techniques in its breeding program to develop cultivars (varieties) resistant to tobacco budworm.

The cultivar 'DES 119' is presently being grown on a large acreage in the Mid-South. Using the larval infestation technique, we evaluated DES 119, during its various stages of development, and reported its resistance levels. When the cultivar was released by the breeder, it was described as being tolerant to tobacco budworm (Bridge, 1986b).

Rapid progress towards developing cultivars highly tolerant to tobacco budworm without any loss in yield or agronomic and fiber properties now should be possible. Public research scientists in USDA's Agricultural Research Service, and in the state agricultural experiment stations have developed the techniques and germplasm necessary for this progress. Germplasms with the desired combinations of resistance, yield, agronomic and fiber properties have been released; they have been registered by the Crop Science Society of America since 1981, with most of it in 1984 and 1988. Many of the cotton lines listed in Table 14 carry these combinations (Bourland, 1987, 1988; Bridge, 1986a,b; Jenkins *et al.*, 1984; Jenkins *et al.*, 1988a,b,c; Jones *et al.*, 1988b; Mahill *et al.*, 1984; Stokes and Sappenfield, 1981; Stringer *et al.*, 1983; Stringer *et al.*, 1987).

There is no reason why high yielding cultivars with high levels of tolerance to tobacco budworm cannot be developed (Hsieh *et al.*, 1987; Jenkins *et al.*, 1987; Jones *et al.*, 1987; Stringer *et al.*, 1987). The DES 119 cultivar is a start in this direction. It is up to the commercial cotton breeders to take advantage of this available germplasm in developing other suitable cultivars (varieties).

In addition to these programs, a number of genetic engineering firms are inserting several constructs of the δ-endotoxin gene from *Bacillus thuringiensis* Kurstaki into advanced strains of cotton. In 1990 public research scientists in cooperation with Monsanto Agricultural Company evaluated five cotton strains into which the *B.t.* gene had been genetically engineered. When all pests were controlled, these strains were equal in yield to the non-transformed parental cultivar Coker 312. This shows that the *B.t.* gene insertion did not have a detrimental effect on yield. When pest insects were allowed to damage the plots, very little damage was found in the transgenic strain plots; whereas, extensive bollworm/tobacco budworm; pink bollworm; cotton leafperforator; and saltmarsh caterpillar, *Estigmene acrea* (Drury). Smaller bolls and seed as well as some changes in lint percentage and some fiber properties were observed in the transgenic strains (Jenkins *et al.*, 1991; Jenkins *et al.*, 1993; Micinski and Caldwell, 1991; Benedict *et al.*, 1991, Gannaway *et al.*, 1991; Wilson and flint, 1991; Williamson and Deaton, 1991).

In 1989, scientists with USDA's Agricultural Research Service and with the genetic engineering company Argracetus conducted a field evaluation of four strains containing the *B.t.* gene. The expression of the *B.t.* gene in these strains was not at a level that offered any control of bollworm/tobacco budworm in field plots. Yields of the transformed strains were good; bolls and seed were smaller and lint percentage higher than in the non-transformed parental Coker 312 strains (Jenkins *et al.*, 1991).

When developing strains with high gossypol as the mechanism for resistance to bollworm/tobacco budworm, the breeder must attempt to keep a low level of gossypol in the seed and at the same time increase gossypol to an acceptable level for resistance in the square. This does not seem to be an insurmountable obstacle. No published data were found on the level of gossypol in the seed of recently developed germplasms which are resistant to tobacco budworm (Table 14). It may be possible to develop a cultivar with glands in the square and no glands in the seed (Altman *et al.*, 1987; Dilday *et al.*, 1982; and Dilday, 1986). We know that gossypol and related compounds are involved in resistance in some lines; however, in others much of the resistance is not due to gossypol. If large acreages of high-gossypol cotton are grown, it is likely that a strain of bollworm/tobacco budworm tolerant of higher levels of gossypol would be selected. A strain with higher tolerance to gossypol has been developed through direct selections in the laboratory; however, this strain was 38 percent less fertile than the control strain (Raulston *et al.*, 1985). Thus, in this instance there were opposing forces operating. The number of generations out of the total generations each year that the species would be under selection pressure from high gossypol cotton is also a major consideration. There are several instances of selection for resistance to insecticides in bollworm/tobacco budworm. Researchers in host plant resistance should expect resistance to gossypol to develop and be prepared with other sources of resistance. This goal is already being considered as all the germplasms or cultivars tolerant to tobacco bud-

Table 14. Registered lines of cotton resistant to bollworm/tobacco budworm[1].

Registration No.	Cotton line	Type	Originator	Year registered
162	BW 76-31	Germplasm	Stokes & Sappenfield	1981
242	MDH-118	Germplasm	Mahill *et al.*,	1984
243	MDH-121	Germplasm	Mahill *et al.*,	1984
244	MDH-126	Germplasm	Mahill *et al.*,	1984
245	MDH-128	Germplasm	Mahill *et al.*,	1984
246	MHR-1	Germplasm	Jenkins *et al.*,	1984
88	DES-119	Cultivar	Bridge	1986b
313	LaHG 063	Germplasm	Jones *et al.*,	1988b
314	LaHG 065	Germplasm	Jones *et al.*,	1988b
315	LaHG 660	Germplasm	Jones *et al.*,	1988b
316	Miscot 7913-51	Germplasm	Bourland	1988
317	Miscot 7913-83	Germplasm	Bourland	1988
318	Miscot 7913-84	Germplasm	Bourland	1988
345	MHR-10	Germplasm	Jenkins *et al.*,	1988b
346	MHR-11	Germplasm	Jenkins *et al.*,	1988b
347	MHR-12	Germplasm	Jenkins *et al.*,	1988b
348	MHR-14	Germplasm	Jenkins *et al.*,	1988c
349	MHR-15	Germplasm	Jenkins *et al.*,	1988c
350	MHR-16	Germplasm	Jenkins *et al.*,	1988c
351	MHR-17	Germplasm	Jenkins *et al.*,	1988a
352	MHR-18	Germplasm	Jenkins *et al.*,	1988a
	PD 875	Germplasm	Culp *et al.*,	1979
	PD 895	Germplasm	Culp *et al.*,	1979

[1]Registered with Crop Science Society of America, 677 South Segoe Road, Madison, Wisconsin, 53711.

worm are not high in gossypol. Our data show that evasion, through early, fast fruiting is also a major component of the resistance in several of these germplasms.

For several years, researchers have cooperated in two Regional Evaluation Tests. One of these involves strains being developed for tolerance to tobacco budworm, and the second involves strains being developed for early, short-season, production. At the Mississippi State location, we have conducted each test under conditions of full protection from insects and with a uniform artificial infestation of tobacco budworm. In some years, one or two other locations have had sufficient natural infestations of bollworm/tobacco budworm to evaluate resistance as well as agronomic performance. Progress has been made in developing high yielding, resistant strains. In 1978, the four highest yielding strains in the bollworm/tobacco budworm test produced only 86 percent of the yield of 'Stoneville 213', the check cultivar. Average yields of the top four were 91, 92, 105 and 114 percent of Stoneville 213 in 1982 through 1985, respectively, when bollworm/tobacco budworm were controlled. When they were allowed to damage the plots, yields of these same strains were 116, 103, 144 and 267 percent of 'Stoneville 213' in 1982-1985, respectively. Thus, progress also has been made in tolerance to tobacco budworm (McCarty, 1987).

In 1987 at Mississippi State, Mississippi, yields of strains in the bollworm/tobacco budworm test ranged from 11 percent less than 'Stoneville 213' to equal when insects were controlled; when high levels of tobacco budworm were allowed to develop, the range was 22 percent to 55 percent higher than 'Stoneville 213' (Table 15). In a 1987 evaluation of early, short-season strains at Mississippi State, Mississippi, yields were from three percent less to eight percent more than 'Stoneville 213' when insects were controlled, and from 15 to 29 percent higher when tobacco budworms were allowed to develop in the plots (Table 16).

Crop damage from infestations of tobacco budworm larvae varies during the growing season. In general, infestations of larvae during the early stages of fruiting result in lower yields and delayed maturity; whereas, mid-season to late-season infestations have little or no effect on yield or maturity (McCarty *et al.,* 1982b; McCarty *et al.,* 1986a). These differences are related to the manner in which the cotton plant produces bolls. Most (65 percent) of the yield of cotton is produced from bolls at the first position on fruiting branches; bolls at position two account for an additional 20 percent of the yield (Knight *et al.,* 1988; Jenkins *et al.,* 1990a,b). There are differences among cultivars in the number of bolls produced on each fruiting branch. These differences translate into fruit being set at different times during the season by different cultivars. Thus, one

Table 15. Yield of selected strains of cotton from 1987 regional test for tobacco budworm resistant strains grown at Mississippi State, Mississippi with and without tobacco budworm. (From: Regional Cotton Variety Test, 1987. Processed by National Cotton Variety Testing Program, USDA, ARS, P. O. Box 19687, New Orleans, Louisiana 70179.)

Strain	Developer	Lint yield: With tobacco budworm	Lint yield: Without tobacco budworm
		lbs/acre	
ST HG-6-1	Stoneville Pedigreed Seed Company	815	1050
La HG 810065	J. Jones	918	1108
La HG 810060	J. Jones	898	1019
Miscot 7913-835	F. Bourland	759	1005
Miscot 7913-51H	F. Bourland	721	1128
ST 213 Check	Stoneville Pedigreed Seed Company	590	1127
LSD .05[1]		189	198

[1]Least significant difference required for significance at .05 level.

Table 16. Yield of selected strains of cotton from 1987 regional test of early, short season strains grown at Mississippi State, Mississippi, with and without tobacco budworm. (From: Regional Cotton Variety Test, 1987. Processed by National Cotton Variety Testing Program, USDA, ARS, P. O. Box 19687, New Orleans, Louisiana 70179.)

Strain	Developer	Seed cotton yield	
		With tobacco budworm	Without tobacco budworm
		lbs/acre	
ST 6413	Stoneville Pedigreed Seed Company	3431	4133
DES 936	Bridge	3977	4029
Coker 84-610	Coker Pedigreed Seed Company	3276	4040
ST 7913	Stoneville Pedigreed Seed Company	3811	3858
ST 213 Check	Stoneville Pedigreed Seed Company	3456	3759
LSD .05[1]		1373	709

[1]Least significant difference required for significance at .05 level.

should expect different levels of tolerance to tobacco budworms among cultivars (Jenkins, *et al.*, 1990a,b; Jenkins *et al.*, 1986; McCarty *et al.*, 1986a).

The cotton plant possesses structures called capitate hairs on both surfaces of leaves. Strains differ in the density of capitate hairs (Bryson *et al.*, 1983; Kosmidou-Dimitropoulou *et al.*, 1980). These are secretory (associated with secretion) hairs and may be involved in resistance. However, in a survey of 29 cotton lines varying in resistance to tobacco budworm, no association was found between density of capitate hairs and growth of tobacco budworm larvae (Bryson *et al.*, 1983).

Glandless cottons have the potential to increase the value of seed products through increased utilization in feed and food products for nonruminants, including humans. Most research indicates that glandless cottons are more susceptible to bollworm/ tobacco budworm than glanded cottons. However, this is not true for all glandless lines. Some glandless lines are no more susceptible than standard glanded cultivars (Meredith *et al.*, 1979a) or than isolines of glanded cotton (Jenkins *et al.*, 1966; Oliver *et al*, 1967).

PINK BOLLWORM

The pink bollworm is the most serious insect pest in many cotton growing areas of the world (Noble, 1969). In the United States, at present, it is a pest of economic importance in the irrigated areas of western Texas, New Mexico, Arizona, and southern California. It has the potential of becoming an economic pest farther east, but it is largely controlled by a combination of quarantine regulations, cultural practices and early maturing cultivars that ensure a long host-free period (Noble, 1969). It has not become established in the San Joaquin Valley of California as a serious pest. Presumably, the ongoing sterile moth release program that was started in the late 1960s has prevented the pink bollworm from becoming established in the Valley (Henneberry, 1980).

Cotton growers in the irrigated deserts of the West have depended upon full season cultivars, a long growing season and repeated applications of insecticides to produce the highest average lint yields in the United States. However insecticides are becoming less effective, and hence more expensive, because of the development of insecticide resistance in the pink bollworm. Heavy use of insecticides also leads to other problems, including outbreaks of secondary pests and deleterious effects on other organisms. This situation has encouraged growers to consider using short-season production practices and early maturing cultivars. Another development is the use of high levels of gossyplure, the pink bollworm pheromone, for early-season control (Staten *et al.,* 1987). However, this strategy is expensive and is warranted only where pink bollworm populations may become high. A cultivar having natural resistance to pink bollworm would be a welcome addition to the grower's defense arsenal against this insect pest.

Painter (1951) and Niles (1980) reviewed the earlier research on resistance of cotton to the pink bollworm. In this chapter we review recent research and discuss the current state of the art in the development of resistant germplasm.

A wide variety of cotton germplasm has been evaluated in both upland short-staple (*Gossypium hirsutum*) and extra-long staple (*Gossypium barbadense*) cottons, including current and obsolete cultivars, germplasm lines, morphological mutants, and day-neutral and photoperiodic primitive race stocks (Wilson et al., 1981).

Several methods are used to evaluate germplasm. They include: (a) exposing cottons to natural field infestations; (b) infesting field or greenhouse plants with eggs or larvae; (c) releasing moths into the greenhouse or field cages; and, (d) bioassays of insect development on artificial diets to which boll content or carpel wall material have been added. The standard method for evaluating field-grown cottons is to determine percent seed damage caused by pink bollworm as shown on radiographs of seed samples (Wilson and George, 1985). In other tests, we have counted eggs and entrance holes, monitored development time and survival of larvae and pupae, and have weighed pupae.

Upland cottons that have shown natural resistance in the field include nectariless, okra-leaf, super okra-leaf, pilose, high-terpenoid and early maturing germplasm lines and cultivars (Table 1). Other upland cottons that showed resistance were an obsolete American cultivar, 'Coker's Foster 300', an Indian cultivar, 'Laxmi', a cultivar from Pakistan, 'NIAB-78', and five breeding stocks of complex parentage—three from Texas (AET-5, AET-BR-2-1, and AET-BR-2-8) and two from Arizona (7203-14-7 and 7203-14-104) (Wilson *et al.,* 1981; Wilson, unpublished data). Singh and Sidhu (1984) reported that the Indian cultivar 'F414', showed some pink bollworm resistance in the Punjab. Chakravorty *et al.* (1982) reported that 'H-777', a cotton with high tannin and low seed protein, had lower seed damage than three other *Gossypium hirsutum* strains.

On the other hand, *Gossypium hirsutum* strains that had as much or more seed damage than the checks were red plant, late-maturing, glandless and frego-bract; strains carrying exotic cytoplasms from six other *Gossypium* spp. are also included (Wilson *et al.,* 1979; Wilson *et al.,* 1981).

American Pima strains, *Gossypium barbadense,* that showed resistance to the pink bollworm were pilos, okra-leaf, glandless, and Pima dwarf. Pima nectariless unexpectedly did not have less seed damage than 'Pima S-5' or 'Pima S-6' (Wilson *et al.,* 1977, 1981; Wilson, unpublished data). Pima red had significantly more seed damage than the checks.

Sixty of 321 primitive race stocks of *Gossypium hirsutum* evaluated showed some resistance in diet bioassays and 41 of 290 evaluated showed resistance in field plots in Puerto Rico (Wilson *et al.,* 1981) (Table 3). Seven of 41 race stocks showed resistance in field plots in Arizona. A majority of the race stocks that had shown resistance (antibiosis) in the diet bioassays also showed antibiosis when bolls on greenhouse-grown plants were hand-infested with young larvae. Of the seven race stocks selected as most promising in the greenhouse tests, three (T-39, T-167 and T-705) showed antibiosis after pink bollworm eggs had been placed on green bolls in the field (Wilson and George, 1984).

The subsequent focus of the pink bollworm research has been to transfer combined resistance traits into agronomically acceptable cottons. The most immediately useful traits are early maturity, nectariless, and okra-leaf.

A series of nectariless isolines averaged 72 percent as much seed damage and 99 percent as much lint yield as the nectaried counterparts while the comparable series of nectariless, okra-leaf isolines averaged 60 percent as much seed damage and 93 percent as much lint yield (Wilson, 1988). A nectariless, okra-leaf isoline and a nectariless, smoothleaf isoline yielded 13 and 14 percent more lint, respectively, than the nectariless counterpart cultivar, but did not have less seed damage. An early maturing nectariless, okra-leaf germplasm line, WC-12-NL, when compared at two locations and three seasons with a full-season, nectaried, normal-leaf cultivar, Deltapine 61, required 41 percent less insecticide to control the pink bollworm, and yielded 12 percent more lint (Wilson, 1988; Wilson, 1991).

Among the sources of antibiosis, the AET-5 strain and germplasm lines from individual plant selections from T-39 are serving as sources of resistance in the breeding program in Arizona (Wilson and George, 1984). In an experiment which was infested artificially with pink bollworm eggs, the germplasm line that had the lowest seed damage (nectariless, AET-t resistance) had 61 percent as much seed damage, yielded 99 percent as much lint, but was not significantly earlier than Deltapine 90 (Wilson, unpublished). Thus, nectariless and nectariless, okra leaf germplasm lines are available that combine significant resistance to pink bollworm with yield potentials approaching or equalling those of current cultivars (Tables 2, 17, 19). It remains to be seen whether transfer of the sources of antibiosis will add an increment of resistance to pink bollworm.

Eight germplasm lines with some resistance to pink bollworm were registered with the Crop Science Society of America in 1992 (Wilson, 1992). It may not be possible to develop germplasm with enough resistance to pink bollworm to preclude the use of other control measures. On the other hand, even a moderate level of resistance, combined with other non-insecticidal control methods, could allow the grower to produce a crop without the use of insecticides to control pink bollworm.

Table 17. Registered germplasm resistant to pink bollworm.[1]

Registration No.	Cotton line	Type	Originator	Year registered
305	WC-10NL	Germplasm	Wilson	1987
306	WC-11NSSL	Germplasm	Wilson	1987
307	WC-12NL	Germplasm	Wilson	1987
260	AET-5N	Germplasm	Wilson	1986
263	AET-5L	Germplasm	Wilson	1986
264	AET-5NL	Germplasm	Wilson	1986
266	AET-5NSL	Germplasm	Wilson	1986

[1]Registered with Crop Science Soceity of America, 677 South Segoe Road, Madison, Wisconsin, 53711.

COTTON LEAFPERFORATOR

The cotton leafperforator has a complex life history. The first three instars of the larval stage mine inside the cotton leaf, then the third instar emerges to form a one-day resting, or "horseshoe" stage. Fourth and fifth instar larvae feed externally on the leaf and are capable of causing considerable damage (Smith and Flint, 1977).

Fry and Henneberry (1977) and Wilson and Wilson (1975) reported methods of measuring leaf damage by the cotton leafperforator. A convenient method of estimating field damage is to collect mature leaves periodically and count "horseshoes". Data are expressed as the number of "horseshoes" per gram leaf weight, which compensates for differences in leaf size (Wilson and Wilson, 1977).

Resistance in nectariless cotton to the cotton leafperforator was reported by Benschoter and Leaf (1974) and Henneberry *et al.* (1977) (Table 1). George and Wilson (unpublished), however, found no difference between nectariless and the check cultivar or smoothleaf-nectariless stocks and the check cultivar in terms of cotton leafperforator "horseshoes" per gram leaf tissue.

A number of researchers have studied the relationship between cotton-leaf pubescence and the incidence of cotton leafperforator. Rejesus (1968) found no difference in oviposition between glabrous (smoothleaf) Seabrook Sea Island and the upland pubescent 'Coker 100A' (*Gossypium hirsutum*). Two smoothleaf upland strains had more eggs than a pubescent strain and two pilose strains and also more than the Arizona wild cotton, *Gossypium thurberi* (Todaro). Less leaf tissue was consumed on four glabrous strains and on 'Deltapine 16' (semi-glabrous) than on four normally pubescent strains.

Wilson and Wilson (1975) reported that strains that were either more glabrous or more pubescent than the normally pubescent upland cultivars were more resistant to cotton leafperforator. The TM-1 Pilose strain (1100 trichomes per square centimeter as compared to 125 trichomes per square centimeter for normal TM-1) had the lowest populations of cotton leafperforator and the least amount of leaf tissue consumed. Harding and Cowan (1971) reported that cotton leafperforator populations were slightly lower on TM-1 Pilose, and slightly higher on D_2 Smoothleaf-321 than on the hirsute check.

George and Wilson (unpublished) subsequently screened many race stocks, upland breeding stocks, mutants, and cultivars of *Gossypium hirsutum* for cotton leafperforator response. They found no consistent differences in stocks of frego bract, early maturing, high-gossypol, glandless, okra-leaf, super okra-leaf, and AET-cottons.

Harding and Cowan (1971) observed significantly higher populations of cotton leafperforator on red leaf cotton, but not significantly different populations on bronze, yellow-green, or virescent mutants. George and Wilson (unpublished) observed higher numbers of "horseshoes" on red-foliaged *Gossypium hirsutum* race stocks, accessions 1234 and 1235.

Among 34 entries of *Gossypium hirsutum* race stocks, George and Wilson (unpublished) found four with significantly fewer "horseshoes" than the check Deltapine 16. When retested, these same four had significantly fewer "horseshoes" than Deltapine 61, but they also had significantly more leaf trichomes. George and Wilson (unpublished) also screened a number of race stocks and race stock X cultivar derivatives reported to have high levels of condensed tannins in the leaves. In 1979, the number of "horseshoes" was more highly correlated with leaf pubescence than with tannin content. One exception was Texas 1055, which is glabrous and had fewer "horseshoes" than Deltapine-61. In 1980, several glabrous, high-tannin derivatives from T-1055 X Stoneville 213 had significantly fewer "horseshoes" than Deltapine-61. In 1981, none of those retested had significantly fewer "horseshoes" than Deltapine-61. F_2BR-1, a high-tannin cotton from North Carolina, had significantly more "horseshoes" than any other entry.

Wilson *et al.* (1977) reported that in mutants of Pima cotton, red leaf had significantly more "horseshoes" than the Pima S-4 or Pima S-5 checks. Pima Pilose and Young's dwarf Pima had fewer "horseshoes" than the check; but, virescent-7, okra-leaf, glandless and the two monomeric glanded Pimas did not have fewer "horseshoes" than the check. George and Wilson (unpublished) observed fewer "horseshoes" in Pima glandless than in Pima S-5 in a later test.

In summary, heavily pubescent cottons have shown good resistance to cotton leafperforator, glabrous cottons have shown some resistance, and red leaf cottons have been susceptible. Also, there is some indication that the nectariless character and cottons with high tannin levels confer some resistance to cotton leafperforator, but these characters need more testing. The *B.t.* gene in transgenic Coker 312 cotton strains conferred resistance to cotton leafperforator (Wilson and Flint, 1991).

PLANT BUGS

Several species of plant bugs attack cotton. The most prevalent ones in the United States are three species of mirids: the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois); western lygus bug, *Lygus hesperus;* and cotton fleahopper, *Pseudomatoscelis seriatus* (Reuter). Plant bugs are sucking insects and sometimes cause plants to branch abnormally or to shed squares or young bolls. Insecticidal control of plant bugs early in the season can sometimes lead to lepidopterous pests problems later in the season because of the destruction of predators and parasites.

The tarnished plant bug is most important economically in the Mid-South. In 1987, 68 percent of the yield loss caused by tarnished plant bug was in the Mississippi Delta and the rest was in other parts of Mississippi and Louisiana (King *et al.,* 1988). Unfortunately, a number of cotton mutants that are useful for resistance to other insects are susceptible to tarnished plant bug, as follows: glabrous (Jenkins *et al.,* 1977; Meredith and Schuster, 1979; Bailey, 1982); okra-leaf and super okra-leaf (Jones, 1982); frego-bract (Schuster and Frazier, 1977).

Fortunately, the nectariless and rapid fruiting traits confer some resistance to tarnished plant bug (Bailey *et al.,* 1980; Bailey, 1982; Bailey *et al.,* 1984). Therefore, breeding strategy has been to combine nectariless with susceptible traits to ameliorate the susceptibility (Jones, 1982; Milam *et al.,* 1982; Jones, 1983). A number of racestocks and various accessions of upland cotton have also shown resistance to tarnished plant bug (Table 18).

The tarnished plant bug has less preference for high gossypol cottons (Schuster and Frazier, 1977). Glandless strains varied in susceptibility to tarnished plant bug. Most of the glandless strains that suffered the least loss in yield, however, were also nectariless, hirsute, or rapid fruiting (Table 18) (Meredith *et al.,* 1979a). Two germplasm lines and one cultivar have been registered that have resistance to tarnished plant bug (Table 19).

The western lygus bug is an economically important pest in California, Arizona, New Mexico and western Texas. In the San Joaquin Valley of California, it is the most important pest in some years, but not in others. For example, in 1986, it caused a estimated loss of over 59,000 bales of lint, but in 1987, no loss was reported (King *et al.,* 1987, 1988).

The western lygus bug apparently feeds on cotton when preferred hosts, primarily alfalfa, are not available. The adults are mobile and may move into the cotton crop when alfalfa is cut, or when hosts are harvested or dry up as the season progresses. Nymphs are much less mobile than adults and may cause considerable damage.

Tingey et al. (1975a) found resistance to the western lygus bug in a number of *Gossypium hirsutum, Gossypium arboreum* L. and *Gossypium barbadense* strains. Several workers have observed resistance to this insect in nectariless cotton (Benedict *et al.,* 1981; Henneberry *et al.,* 1977; Benedict *et al.,* 1982).

The data are conflicting on the response of the western lygus bug to glabrous cotton. Tingey *et al.* (1975a) reported that growth, survival and nymphal emergence were no different on Bayou SM-6 glabrous than on Acala SJ-1. Wilson, R. L. and F. D. Wilson (unpublished) observed lower populations of adults (but not nymphs) on a Stoneville glabrous strain, and also on a glabrous, nectariless strain. George and Wilson (unpublished) observed that more squares were shed on glabrous than on hirsute isolines, but genetic background effects were operating. Benedict *et al.* (1982) reported that glabrous reduced oviposition (egg laying) by 30 percent, but increased growth rate and survival. The pilose trait caused increased oviposition, but decreased growth rate and survival. Tingey *et al.* (1975a) also reported lower nymphal weight on pilose than on a normally hirsute cultivar (Table 18).

Table 18. Summary of selected evaluations for resistance to *Lygus* spp. in cotton.

Resistant source and type	Reference
Antibiosis	
Nectariless	Benedict *et al.*, 1981
Pilose, DES-ARB-16, DES-HAF-277, DES-HAMS-277, DES-HAMS-16, DES-HERB-16, DES-LONG-227, DES-LONG-16, *Gossypium arboreum*, SA203, SA117, CB3031, T-110, T-254-24-14, 247-1-6-HGSm	Tingey *et al.*, 1975a,b
Yield under tarnished plant bug infestation	
Day neutral selections from T-78, 113, 158, 195, DES-ANOM-16, Bulgarian 3279, Hopi NM, Timok 811	Jenkins & Parrott, 1976
JPM-781-78-3	Jenkins *et al.*, 1979a
Pubescence	Meredith *et al.*, 1979
Glandless lines with either nectariless, hirsute or rapid fruiting	Meredith & Schuster, 1979
DES-35, DES-119	Bridge, 1986a,b

Table 19. Summary of resistant cotton germplasm and races available to breeders to use in developing resistant cultivars.

	Released to public		
Trait or pest	Resistant germplasms	Resistant cultivars	Number of race accessions
Pink bollworm	7		99
Bollworm/tobacco budworm	20	1	56
High gossypol content			33
Spider mite			6
Plant bug	2	1	11
Boll weevil	20		59
Early short-season strains	7		
Nectariless strains	17	1	
Frego bract strains	8		
Smooth leaf strains	10		
Okra-leaf strains	8		
Okra-leaf frego bract strains	11		
Nectariless frego strains	8		
Nectariless okra-leaf	7		

Several workers reported that frego bract and glandless strains are more susceptible to western lygus bug than their normal counterparts (Leigh *et al.*, 1971; Tingey *et al.*, 1975b). Benedict *et al.* (1981) found no difference in oviposition on glanded and glandless isolines. Leigh *et al.* (1985) compared 52 glandless breeding lines with the check cultivar, Acala SJ-2, and found 20 that did not support significantly higher numbers of insects. In a second test, nymphal growth rate and insects per terminal were not higher on 5 of 37 glandless strains (including the 20 selected ones) than on the check, Acala SJ-2. Those authors concluded that it should be possible to select glandless breeding lines that are no more susceptible to western lygus bug than the glanded Acala SJ-2.

Benedict *et al.* (1982) found a number of cotton strains, among 600 evaluated, that showed an unknown type of chemical resistance to western lygus bug.

The cotton fleahopper is a pest primarily in the southwestern United States. In 1986 and 1987, the highest yield losses attributed to cotton fleahopper occurred in western and northwestern Texas (King *et al.*, 1987, 1988).

Considerable controversy has arisen over the benefits of glabrous versus pubescent cottons in decreasing cotton fleahopper populations and plant damage. Lukefahr *et al.* (1970) showed that pilose cottons harbored more cotton fleahoppers than less densely pubescent strains, which in turn supported more than the glabrous standard, 321. Walker *et al.* (1974) agreed that glabrous cottons had fewer cotton fleahoppers than did pubescent cottons, but also sustained greater damage and more yield loss in untreated versus treated plots because of hypersensitivity. They also showed that pilose cotton had more cotton fleahoppers than the other phenotypes, but showed good tolerance as reflected in a lower yield loss.

Lukefahr *et al.* (1976) and Lukefahr (1975) attributed the yield loss shown by certain glabrous cottons not to cotton fleahopper, but to leafhoppers (primarily *Empoasca* spp.). For example, Bayou SM-1 had fewer accumulative blooms than the pubescent 'Stoneville 7A' at Waco, Texas, where leafhopper populations were much higher in the glabrous strain, but not in the Rio Grande Valley, where leafhopper populations were uniformly low.

Nectariless strains have supported lower cotton fleahopper populations in some experiments, but not in others. Cowan and Lukefahr (1970) found no difference in nectaried strains in glabrous background. On the other hand, several workers have reported (or have cited earlier works) significant reduction of cotton fleahopper on nectariless cottons (Meredith, 1976; Schuster *et al.*, 1976; Schuster and Frazier, 1977). Liddell *et al.* (1986) showed that eight nectariless strains yielded only 47 to 73 percent as much lint at first harvest, and 76 to 86 percent as much at final harvest in heavily cotton fleahopper infested plots as in protected plots. In contrast, the most susceptible cultivar, 'Lankart LX 571', yielded 33 percent as much at first harvest and 66 percent as much total lint. Comparable figures for the most resistant strain, pilose, were 119 percent at first harvest and 91 percent total lint.

Lukefahr (1975) reported that two high gossypol strains had 70 percent fewer cotton fleahopper nymphs and 50 percent fewer total cotton fleahoppers than did

'Stoneville 7A'. Young *et al.* (1986) observed that a frego bract strain was preferred for oviposition over several normal-bract cultivars.

LEAFHOPPERS (JASSIDS)

Leafhoppers or jassids (*Empoasca* spp.) are widely distributed and a number of species occur as pests of cotton in many African countries, Australia, China, India, Pakistan, Philippines, United States and others (Painter, 1951). Certain species that occur in Africa, India, Pakistan and Australia are particularly destructive (Niles, 1980).

Fortunately, resistant germplasm is available and has been used extensively. In fact, host plant resistance is the major control strategy where leafhoppers are important economically. Cotton cultivars with dense leaf pubescence, especially on the adaxial (lower) surface, are highly resistant to leafhoppers (Bhat *et al.,* 1982). Hair density and hair length are both important. Leaf pubescence apparently interferes with oviposition. The highest level of resistance occurs when pubescence is high on both the midrib and the lamina.

Unfortunately, pubescent cultivars are undesirable for a number of reasons, including the occurrence of more trash in the lint and susceptibility to other insects such as whiteflies, aphids and bollworms (Bhat *et al.,* 1982; Butler and Wilson, 1984).

Bhat *et al.* (1982) crossed two densely pubescent, leafhopper-resistant cotton cultivars of *Gossypium hirsutum* with a less hairy, susceptible cultivar. In the two F_2 populations, 3 and 0.4 percent of the plants, respectively, combined a high level of leafhopper resistance with relatively sparse pubescence. Thus, it appears possible to separate leafhopper resistance from high levels of pubescence.

Bhat *et al.,* (1981a,b) found that two Asiatic strains of cotton (*Gossypium arboreum*) had the highest level of leafhopper resistance and the lowest amount of peroxidase activity and tannin, but not the lowest level of protein, in the leaves. Two resistant American cotton strains (*Gossypium hirsutum*) had the lowest enzyme activity and protein and tannin content, four moderately resistant strains had intermediate levels, and six susceptible strains had high levels.

Bailey (1982) showed in Mississippi that glabrous cottons had higher populations of leafhoppers (*Empoasca* spp., primarily) and *Lygus* spp., and lower lint yields than did hirsute cottons. Nectariless strains supported slightly lower leafhopper, plant bug, and predator populations; they yielded more lint than did nectaried strains.

WHITEFLIES

Two species of whitefly predominate as pests of cotton: they are the bandedwinged whitefly, *Trialeurodes abutilonea* (Haldeman), and the sweetpotato whitefly, *Bemisia tabaci* (Gennadius). However, there are others (Leigh, 1984). The bandedwinged whitefly is found throughout the Cotton Belt and is sometimes a pest of economic consequence in the Mid-South and Southeast (Clower, 1984; Jones *et al.,* 1975; Lambert, 1984; Lambert *et al.,* 1982b). The sweetpotato whitefly is widely distributed in warmer parts of the world and attacks many crops (Berlinger, 1986). In the United States, it is found mainly in the irrigated low-elevation deserts of Arizona and southern California.

Whiteflies secrete honeydew which results in sticky fiber and may also attract fungi which will discolor the fiber. In addition, the sweetpotato whitefly is the vector of a number of diseases of cotton and other crops (Butler *et al.*, 1985; Duffus and Flock, 1982).

Butler and Wilson (1984) observed significantly fewer bandedwinged whitefly on glabrous isolines, and on the semi-glabrous check cultivar, Deltapine 61, than on pubescent isolines. Lambert *et al.* (1982b) showed that less pubescent cultivars (among 35 total) generally supported smaller colonies of bandedwinged whitefly and allowed lower adult emergence, but there were some exceptions to this pattern.

The glabrous trait is the most important trait found thus far that reduces sweetpotato whitefly populations on cotton plants (Berlinger, 1986; Butler and Henneberry, 1984, 1986). Butler and Wilson (1984) found significantly fewer whitefly adults on sticky traps placed in glabrous isolines than in pubescent isolines in the AET-5 genetic background. Differences were not significant, however, between nectariless and nectaried isolines, and okra-leaf and normal leaf isolines. In another experiment planted in the same field, semi-glabrous isolines did not have lower whitefly populations than pubescent isolines. On the other hand, the semi-glabrous check cultivar, Deltapine 61, had lower mean numbers of whiteflies than all the other cottons in both experiments. In a commercial California cotton field, genetic background and level of pubescence both influenced adult whitefly populations. Two pubescent Deltapine cultivars averaged 914 adults per trap, two pubescent Stoneville cultivars averaged 691 per trap, and five semi-smoothleaf Deltapine cultivars averaged 493 per trap. H. M. Flint (Personal communication, USDA, ARS Western Cotton Research Laboratory, Phoenix, Arizona) found that the densely pubescent Stoneville 506 (85 trichomes per square centimeter on the sixth leaf from the apex) had fewer whitefly nymphs than expected, and the pubescent Centennial (42 trichomes per square centimeter) had more, based on the level of pubescence alone. Both pubescent cottons, as expected, had more nymphs than the semi-glabrous Deltapine 20 (0.2 trichomes per square centimeter). Butler *et al.* (1986) showed that, in 'Stoneville 825' genetic background, the pubescent isoline had the most adults and eggs, the semi-glabrous isoline had intermediate numbers, and the glabrous isoline had the lowest numbers. Also, number of whitefly adults and eggs were significantly lower on leaf halves that had been shaved with an electric razor than on the unshaven halves of leaves of the pubescent Stoneville 825.

Bindra (1985) reviewed the very serious whitefly problem in the Sudan. He concluded that damaging populations of whitefly (i.e., high enough to lower fiber grades through stickiness and discoloration) coincided with the introduction of the Lambert cultivars of extra long staple cotton, *Gossypium barbadense,* that had closed canopies and large leaf areas. The older, Sakel-type cultivars had open canopies and smaller leaf areas which had the advantage of permitting a less favorable (warmer, drier) microclimate within the canopy and which also allowed better penetration of insecticide. Also, the introduction of the closed canopy, large leaf area, Acala cottons (*Gossypium hirsutum*) aggravated the whitefly problem. A recent release of Sudac-K, a glabrous, super okra-leaf Acala cultivar, and anticipated releases of similar *Gossypium barbadense* cultivars should, in Bindra's opinion, reduce the whitefly problem significantly.

Berlinger (1986) stated that resistance to whitefly would be enhanced by glabrousness, a more open canopy (i.e., okra-leaf or super okra-leaf) and, based on Berlinger *et al.*, 1983 earlier work, a low pH in leaf sap.

In other studies, okra-leaf did not increase resistance to sweetpotato whitefly. Butler *et al.* (1986) studied six pairs of okra-leaf/normal-leaf isolines and found significantly fewer adult whiteflies only on 'Stoneville 7A' okra-leaf, significantly more on two others, and no differences on the other three. The okra-leaf cottons that Butler *et al.* (1988) and Khalifa and Gameel (1982) reported as having whitefly resistance were also glabrous.

The sweetpotato whitefly transmits a number of viruses, among them the cotton leaf crumple virus (Brown and Nelson, 1984). This disease has been present in the desert cotton growing areas of the United States for a number of years, but has increased within the past few years because of the increased incidence of whitefly. The commonly grown Deltapine cultivars are susceptible to cotton leaf crumple virus (Wilson *et al.*, 1989). Fortunately, the Cedix cultivar, developed in El Salvador, is highly resistant or immune to this virus. A nectariless cultivar (Conal) from Nicaragua also is apparently resistant, as are a number of other breeding lines from Nicaragua. A breeding program is underway to transfer the resistance into United States cultivars.

THRIPS

Lambert (1985) lists several species of thrips as economic pests of seedling cotton and five as economic pests of the mid-season and late-season crop. Several thrip species may be beneficial because they are predaceous (prey on) on other thrips and on mites. The western flower thrips, *Frankliniella occidentalis* (Pergande), shares this distinction, but can also be a pest of cotton throughout the season. The western flower thrips, long regarded as a cotton pest only in the western United States, apparently has now achieved pest status through the United States Cotton Belt.

Abdel-Bary *et al.* (1968) reviewed the literature up to that time on the response of cotton germplasm to onion thrips, *Thrips tabaci* Lindeman, attack and concluded that varietal differences existed. The 'Empire' cultivar (*Gossypium hirsutum*) and some of its derivatives seemed to have the most thrips resistance. Ballard (1951) attributed the resistance of Empire to the occurrence of dense pubescence on young leaves, and the susceptibility of 'Hi-Bred' to its glabrous leaves. Cultivars with intermediate pubescence varied widely in resistance, suggesting mechanisms other than pubescence.

In Egypt, 'Bahtim 101' and 'Menoufi', two extra long staple cultivars of *Gossypium barbadense,* had less seedling damage than another extra long staple cultivar, 'Bahtim 185', and an upland cultivar (*Gossypium hirsutum*), 'Coker 100' (Abdel-Bary *et al.*, 1968).

Abdel-Gawaad *et al.* (1973) measured the thickness of various cotyledon leaf-cell layers and counted numbers of onion thrips on sixteen cottons. Number of thrips was negatively correlated with the thickness of the lower epidermis. 'Giza 31', the exception, had thinner than average lower epidermis, but a lower than average population of thrips.

Rummel and Quisenberry (1979) showed that young plants, about 28, 35, and 42 days old, of 'Deltapine 14' pilose (densely pubescent) suffered no significant loss of leaf area caused by leaf feeding of thrips (several species, proportions of each not determined). However, leaf areas of the other five cottons—Tamcot SP-37, Tamcot SP-21, Deltapine 14 okra-leaf and Paymaster B8-3502—were reduced significantly. The pubescent Tamcot SP-37 did not suffer as much leaf area loss as the glabrous Tamcot SP-21.

Mauney *et al.* (1980) attributed one cause of shed of small squares to a soft rot caused by a bacteria that is presumably introduced into the square by thrips. Squares with abnormal numbers of involucral bracts (Wilson and Stapp, 1979), the so-called four-bract squares, apparently allow entrance of the thrips into the squares more readily than do normal, three-bract squares. Mauney and Henneberry (1984) observed that, over three seasons, thrips accounted for an average of 18 percent of the total square shed from early June to mid-July at Phoenix, Arizona, but only 4 percent from mid-July to early August.

Flint *et al.* (1989) determined causes of square shed in 'Deltapine 61' (a nectaried, semi-glabrous, normal-leaf shape cultivar) with those in WC-12NL (a nectariless, pubescent, okra-leaf shape germplasm line) (Wilson, 1987). Deltapine 61 had a significantly higher percentage of four-bract squares on the plant (10 percent) and on the ground (9 percent) than did WC-12NL (1 and 3 percent, respectively). Deltapine 61 also lost more squares due to thrips damage (30 percent of three-bract squares and 54 percent of four-bract squares shed were caused by thrips) than did WC-12NL (22 and 26 percent, respectively). In another experiment reported in Flint *et al.* (1989), Deltapine 61 and 'Deltapine 77' had higher percentages of four-bract squares, more total square shed, and more squares lost from thrips damage than did Stoneville 825. Percentages of three-bract squares lost due to thrips damage averaged 29 percent in the Deltapine cultivars and 21 percent in Stoneville 825. Percentages of four-bract squares lost due to thrips damage averaged 74 percent in the Deltapine cultivars and 30 percent in Stoneville 825.

SPIDER MITES

Relatively little research has been done on host plant resistance to spider mites, *Tetranychus* spp. The Acala and Pima cultivars seem to be more tolerant to spider mites than others. An extensive evaluation program indicated that 86 accessions of the 686 tested in the upland, *Gossypium hirsutum*, race collection, almost all 195 evaluated in the extra long staple, *Gossypium barbadense* collection, plus several species and interspecific hybrids were resistant (Table 20) (Schuster *et al.*, 1972a,b; Schuster *et al.*, 1973; Schuster and Maxwell, 1976). Cross resistance to twospotted spider mite *Tetranychus urticae* Koch and desert spider mite, *Tetranychus desertorum* Banks, exist in some cotton lines (Schuster and Cherry, 1975). Recent research indicates that strawberry spider mite, *Tetranychus turkestani* Ugarov & Nikolski produces a toxin induced injury in cotton (Brito *et al.*, 1986).

Table 20. Summary of selected evaluations for resistance in cotton to the twospotted spider mite.

Resistant source	Reference
Pima S-2, Pima S-4	Schuster *et al.*, 1972a,b,c
Gossypium barbadense, Gossypium australe, Gossypium lobatum, Pima S-1, S-2, S-3, S-4	Schuster *et al.*, 1972b
10 obsolete cultivars	Schuster *et al.*, 1973
86 *Gossypium hirsutum* race stocks (686 tested)	Schuster *et al.*, 1973 Schuster & Maxwell, 1976
184 *Gossypium barbadense* strains (195 tested)	Schuster *et al.*, 1973 Schuster & Maxwell, 1976
Gossypium hirsutum x Gossypium anomalum, Gossypium hirsutum x Gossypium raimondii	Schuster *et al.*, 1973

SUMMARY

We are at a threshold in the development of cotton cultivars (varieties) resistant to major pests. In the past several years, resistant, high yielding germplasms have been released and registered from public research programs (Tables 4, 14, 17). These germplasms are available to private seed companies for their use. The techniques for evaluating these germplasms have also been made available. Genetic engineering research to move the δ-endotoxin gene into cotton from *Bacillus thuringiensis* has progressed swiftly in the private sector. In the future, genetic engineering techniques will play an increasingly important role in broadening the germplasm base of resistance to pests. Field tests in 1990, 1991, and 1992 showed that the *B.t.* gene when inserted in cotton would provide significant levels of protection from damage by several lepidopterous insects.

Data from replicated field trials have shown that the nectariless trait provides a useful level of resistance to lepidopterous insects and plant bugs. The trend towards the development of early-maturing, fast fruiting cultivars will significantly reduce a number of insect problems now faced by growers. While the glabrous, okra-leaf, and frego bract traits confer resistance to some insects and susceptibility to others, breeders are combining traits that will help to ameliorate susceptibility. For example, frego bract confers resistance to boll weevil but susceptibility to tarnished plant bug. Germplasms that combine early maturity and the nectariless trait with frego bract are resistant to boll weevil but no more susceptible to tarnished plant bug than are normal-bract cottons.

The level of resistance to bollworm/tobacco budworm is high in several of the germplasms registered in the past few years. At least one major seed breeding firm in the United States is actively using these germplasms and techniques to develop bollworm/tobacco budworm-resistant cultivars. Three cultivars already on the market, DES 119, 'Stoneville 506' and 'Deltapine 50' have a useful level of tolerance to bollworm/tobacco budworm.

The appearance of early-maturing, rapid fruiting cultivars in the past several years signals the beginning of a concerted effort to breed cotton plants that evade pests and thus have effective field resistance to pests. In the next few years, new cultivars with resistance to bollworm/tobacco budworm, plant bugs and pink bollworm should appear on the market. Also, significant progress should be made in identifying resistant germplasm and management strategies that will help reduce problems from other major cotton pests. In fact, the new cultivars and resistant germplasms will form the foundation for even more successful methods of pest control. Control of cotton insects may not be possible without the continued use of insecticides to supplement other control methods. On the other hand, quantities of insecticides used with be reduced significantly as resistant germplasm and other alternative control methods are integrated into production systems.