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# Sticky Cotton: Causes, Effects, and Prevention

E. Hequet, T.J. Henneberry, and R.L. Nichols

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## Abstract

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Adherence of contaminants and lint to cotton processing equipment is called “stickiness,” and the contaminated lint is “sticky cotton.” Sticky cotton is a worldwide problem, increasing as cotton processing machinery is refined because high-speed, large-volume processing of lint requires cleaner cotton. Honeydew, the sugar-containing excretions of certain insects, mainly whiteflies and aphids, are the most frequent cause of sticky cotton. These papers discuss the effects of sticky cotton on the industry, identify sources of contaminants, and describe the major insect pests and their biology, population development, and interactions with the cotton plant. Preventing plant stress and reducing insect population development are important control tactics. Other approaches include planting smooth-leaf varieties, limiting cotton production to a single fruiting cycle, timely harvesting, and timely destruction of all crops that are hosts for honeydew-producing insects. Selective insecticides can suppress honeydew-producing insects, but insecticide resistance is a continuing threat.

Keywords: *Aphis gossypii*, bandedwinged whitefly, *Bemisia tabaci*, boll development, cotton, cotton aphid, cotton boll, cotton history, cotton lint, cotton quality, fiber processing, ginning, H2SD, honeydew, insecticide resistance, minicard, physiological sugars, research, sampling, sticky cotton, sweetpotato whitefly, thermodeceptor, *Trialeurodes*.

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## Preface

E.F. Hequet, T.J. Henneberry, and R.L. Nichols

Cotton (*Gossypium* spp.) lint stickiness is the number one worldwide cotton quality problem. It was recorded as early as 1942 (Husain and Trehan 1942) and accorded recognition as one of the most serious quality problems in the cotton industry beginning in the early 1970s, when Perkins (1971) and Khalifa and Gameel (1982) suggested that stickiness was a limiting factor in cotton production in some cotton-growing countries. The problem received additional attention when the International Textile Manufacturers Federation established a special Honeydew Working Group charged with the objectives of finding appropriate tests to identify plant and insect sugars in cotton lint, evaluate test reliability in determining lint stickiness, and finally to collect and assess available information on cotton stickiness. The excellent review of Hector and Hodkinson (1989) served as a base of information on the subject. These authors also identified a number of large gaps in the available information base and particularly identified the lack of field experimentation to determine the causes and main factors affecting the extent of management of the stickiness problem.

In most cases, cotton lint stickiness is associated with lint contamination from insect honeydew produced by whiteflies and aphids. Populations of sweetpotato whiteflies, *Bemisia tabaci* (Gennadius) Biotype B (= *Bemisia argentifolii* Bellows and Perring), increased to epidemic proportions in cotton in California, Arizona, and Texas beginning in 1986. The cotton stickiness problem became apparent in Arizona in 1991 with associated discounts of up to about 20 cents per pound (454 grams) on cotton lint. Stickiness problems caused by cotton aphids, *Aphis gossypii* Glover, also have occurred recently in West Texas, notably in 1995. Aphids are a chronic management problem in the Mid South, Texas, and California and have been associated with reports of stickiness in cotton lint originating in the arid regions of Texas and the San Joaquin Valley of California.

Sweetpotato whitefly and cotton aphid control costs and decreased gin efficiency are absorbed at the field level. Although difficult to estimate, lint price reductions are imposed on certain areas because they have been sources of sticky cotton. Thus the problem of stickiness tends to affect lint prices over a whole production

area, even when only certain producers within the area are the source of the contamination. Economic losses caused by sticky cotton are also incurred at the mill because of increased running time to produce the same quantity of yarn, increased maintenance of processing machinery, and, in severe instances, mill downtime because certain lots of cotton could not be run at all. Refusal of spinning mills to process sticky cotton has inflicted price differentials of more than 10 percent in certain areas.

Thus the problem affects both the producing and manufacturing segments of the industry, and frequently compromises the reputation of cotton merchants. Much of the cotton produced in the Western United States is exported, and loss of export markets is a serious threat to the U.S. economy.

Concern for domestic economic losses and potential loss of foreign export trade has stimulated research resulting in identification of the major sugars found in honeydews. The development of technologies to assess cotton lint stickiness, the determination of relationships between sweetpotato whitefly population density and cotton stickiness, and research on the biology and management of sweetpotato whiteflies and cotton aphids is still ongoing. During the last 10 to 15 years, intensive effort has been expended by the scientific community and the cotton industry to address some of the issues associated with the cotton stickiness problem. Many organizations have contributed to our current knowledge.

Most of the work has been accomplished by USDA-ARS, University of California, University of Arizona, Texas A&M University, the International Textile Center at Texas Tech University, and certain industry cooperators. Much of this research has been achieved in cooperation with Cotton Incorporated and the Sticky Cotton Action Team, an ad-hoc industry working group sponsored by Cotton Incorporated. Invaluable assistance was also obtained from co-operative efforts and information exchange with Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), the French government's sponsored institute for agronomic research, and with Israeli entomologists through the Binational Agricultural Research and Development agreement and Pakistani entomologists through U.S. Agency for International Development programs.

Although considerable progress has been made, much more needs to be done. In this publication we attempt to update available information of cotton lint stickiness in relation to research contributions since the review of Hector and Hodkinson (1989). We also identify additional needed information. The editors are grateful to all of the contributors, reviewers and others that helped in development of this publication.

Some of this information has been published in various journals and meeting proceedings. Much of it has not been published. It is urgent that this information be assembled and synthesized for use by the cotton industry, the scientific community, managers, and administrators. We have participated in approximately a decade of coordinated research that has revealed a great deal about the sources, nature, and effects of sticky cotton and that has determined how to prevent it by field management and how to reduce its negative effects by management at the gin and textile mill. We have learned a great deal about the chemistry and enzymology of insect sugars, the population biology of homopteran pest insects, the design and implementation of practical insect and insecticide resistance management programs; and the principles of theoretical and practical measurement of stickiness for the purpose of management of contaminated cottons in the mill. This bulletin reviews the problem, past and present research results on sweetpotato whitefly and cotton aphid honeydew carbohydrate content, relationships to sticky cotton, and methods of sticky cotton sampling, measurement, and prevention.

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# Chapter 1

## Introduction

*T.J. Henneberry, R.L. Nichols, and E.F. Hequet*

### Early History of the Cotton Industry

Brubaker et al. (1999) reviewed the origin and domestication of New- and Old-World cottons (*Gossypium* spp.) in detail. Although Old-World cottons are still grown in some parts of Africa and Asia, agronomically superior New-World cultivars of *G. hirsutum* (short-staple) and *G. barbadense* (long-staple) dominate world cotton production, and 90 percent of the cottons grown are *G. hirsutum* cultivars (Brubaker et al. 1999).

The point in history where man began processing cotton lint to produce cloth is unknown. Archeological remains of cloth fragments and yarn, attributed to an Old-World cotton, *G. arboreum*, dated to around 4300 B.C., have been recovered from sites in India and Pakistan (Smith and Cothren 1999). Furthermore, a line in a Hindu hymn written in approximately 1500 B.C. refers to “threads in a loom” (Scherer 1916). Scherer also pointed out that the earliest records of man indicate the use of various fibers in the manufacture of cloth. Wool was the principal fiber in western Asia and southern Europe, flax in northern Europe, silk in China, and in India the principal fiber was cotton (Handy 1896). India was the center of the cotton industry for 3,000 years (Scherer 1916). Indian ginning, spinning, and weaving machinery in early times was hand-operated and of the most primitive type.

Cotton was apparently introduced from India into Europe through established trade routes (see May and Lege 1999 for a review). Expertise in wool and other fabric processing contributed to the success of the cotton textile industry following its introduction into Europe. Production of cotton fabrics was, however, severely limited by the supply of yarn. In 1763 James Hargreaves, a cotton weaver from Lancashire, England, invented the first automated spinning machine, which dramatically increased yarn availability. He called it the “spinning jenny.” The machine was driven by hand and worked in the same way as a spinning wheel; that is, discontinuously with spinning and winding in two separate phases. Spinning jennies were later built with 18 to 120 spindles. Cotton industry textile laborers saw this new technology as a

threat to their jobs. During disturbances in 1779, angry home workers, fearing for their livelihood, forced their way into his home and destroyed the jennies.

The first power mill was built in Bombay, India, in 1854. The historical progression of technology from hand harvesting and cottage production of cotton cloth to the development of machine harvesting and high-speed, efficient cleaning, spinning, and weaving methods is well documented (Handy 1896, Scherer 1916, Elliot et al. 1968, May and Lege 1999). Within that history is documented the increasing need for high-quality, clean cottons to accommodate the demand for automated, high-productivity lint-processing machinery that has become increasingly vulnerable to malfunction from the presence of lint contaminants.

### Early Cotton Production and Textile Manufacturing in the United States

American cottons are considered hybrid in origin. Seed planted by the early colonists (Handy 1896) was probably brought to the American cotton belt from many different cotton-growing areas of the world. Origins of a few native varieties, such as Sea Island, Pima, and American-Egyptian are known, but the origin of the vast majority of upland cottons is unknown. Hammond (1897), from historical reports, found mention of wild cottons growing in 1536 in the territories now represented by Louisiana and Texas.

Until the end of the Revolutionary War, the American colonies were completely dependent on England for commercial cotton cloth (Anonymous 1975). Growing hostilities between the colonists and England resulted in a sharp curtailment of cotton supplies to America during the 10 years prior to the “shot heard round the world.” The first official concern about the general lack of textile production capacity in the colonies was noted when the 1775 Virginia Convention at Richmond unanimously passed resolutions that encouraged textile industry development and suggested that all persons having proper lands grow flax, hemp, and cotton in amounts for themselves and with some to spare for others without land resources (Handy 1896). Farmers not serving in the militia were urged to contribute their efforts to the cotton industry. The resolutions further stressed that the needs to achieve America’s goal of self-sufficiency were invention of a machine to separate lint from seed, construction of mills, and searches for new cottons adapted to American agriculture.

The first cotton mill in the United States was built in 1787 in Beverly, MA. However, small-scale home weaving was the predominant practice in the United States until Eli Whitney's invention of the cotton gin in 1793. Cotton production and textile manufacturing increased dramatically following Whitney's invention. For example, in 1790 the United States exported 889 bales; in 1900 exports had increased to more than six million bales (Scherer 1916).

Growth of the textile industry and the import and export of cottons required development of quality standards. Cotton buyers recognized differences in fiber length and strength as well as differences in color, trash, and foreign matter. Standardization, however, was not attempted until passage of the United States Cotton Futures Act in 1914. Cotton standards were established for American-Egyptian and Sea Island cottons in 1918. Staple-length standards were established in 1918, followed by a numerical grading system in 1922. There followed establishment of white cotton grades under the Official Cotton Standards of the United States for domestic cottons in 1922.

On March 4, 1923, the United States Cotton Standard Act was passed by congress for interstate and foreign commerce transactions. The international cotton standards that developed were accepted on August 1, 1924 (Scherer 1916). The universal standards also established extraneous lint impurities (leaf trash, dirt, etc.) as characteristics for consideration in cotton classing. Cotton classing, as described by May and Lege (1999), was accomplished by visual comparison of a bale lint sample with a U.S. Government standard prepared in accordance with the Cotton Standards Act. Staple length was estimated to the nearest 1/32 of an inch of a sample pulled from the bale. Subsequent research has resulted in the development of instrumentation to precisely measure fiber properties. Instrumental measurement of fiber properties and development of the means to store, retrieve, and use these data have resulted in measurable improvement in the cotton classing system.

### **Changes in Cotton Harvesting and Lint Processing**

After World War II, U.S. agriculture and cotton production practices changed rapidly. Cotton production inputs—including increased use of fertilizers, irrigation, plant growth regulators, harvest

aides, and pesticides—greatly increased cotton yields. Until the end of World War II, the use of mechanical cotton harvesting in the United States was negligible, but increased to 23 percent of the acreage by 1955, 85 percent by 1965, and virtually 100 percent thereafter (Colwick and Williamson 1968).

With the advent of mechanical harvesting, increased moisture and trash content in seed cotton became concerns in cotton ginning. Unless the seed cotton was carefully ginned, contaminants could be passed forward to the textile mills. Moreover, during the same period the operating speed of lint processing machinery was increasing to increase the volume of production. The new equipment had lower tolerances for trash or deviations in moisture content. Moreover, adjustments at one point in lint processing could transfer a problem to other stages. For example, in the carding operation, crush rolls were developed to facilitate high-speed fiber alignment and to minimize trash. If sticky cotton were encountered, crush roller pressure could be decreased to reduce lint buildup around leaf trash and seed particles; however, if more trash were allowed to reach the spinning line, stickiness could create problems in that processing area. Since the new equipment ran at increased speeds, fiber processing equipment in the 1970s and 1980s was now more susceptible to lint stickiness than formerly (Gutknecht 1988).

The awareness that the physiology of the cotton plant, its phenology, and its interaction with the environment affected lint quality and fiber characteristics raised additional questions about the scope of the stickiness problem, its possible biotic causes, and means to reduce or eliminate lint stickiness. An early review by Perkins (1971) considered noncellulosic fiber components and the industrial lubricants often used in textile mills as possible sources of lint contamination. A higher than usual content of noncellulosic components in cotton lint is often associated with low fiber micronaire. Low micronaire is often associated with adverse climatic conditions, especially low temperatures during boll development. Low micronaire may also result from misuse of production inputs that may cause excessive vegetative growth and late fruiting, such that a relatively large portion of the harvestable bolls produce relatively immature cotton fibers.

Following a particularly sticky cotton crop from the San Joaquin Valley, CA, in 1977, Perkins et al. (1978, 1979) investigated the role of naturally occurring noncellulosic contaminants in sticky cotton

and reported that the amounts of plant-synthesized noncellulosic contaminants in sticky and nonsticky samples were not significantly different. However, high levels of sugars that were not synthesized by plants were related to high levels of stickiness. The sugars that were not associated with plant metabolism were suspected to have come from cotton aphids (*Aphis gossypii* (Glover)) or sweetpotato whiteflies (*Bemisia tabaci* (Gennadius) Biotype B [= *B. argentifolii* Bellows and Perring]).

Thus insects also were suspected as having a role in cotton lint stickiness. The first observations suggesting that lint stickiness problems might be caused by contamination from secretions from phloem-feeding insects are unknown. However, Husain and Trehan (1942) have been acknowledged as having published the first record. These authors referred to studies conducted from 1931 to 1936 in India where copious amounts of honeydew produced by sweetpotato whitefly nymphs were observed to accumulate on leaves and plant parts and to support the growth of molds. Hadwich (1961) expressed particular concern for lint contamination by cotton aphid honeydew, but also suggested whitefly honeydew as another source of contamination.

In 1980, after increasing concern with cotton lint stickiness, the International Textile Manufacturers Federation established a “Honeydew Working Group” to develop tests for identifying lint stickiness, review current information, and make recommendations for research to solve the problem (Hector and Hodkinson 1989). The Honeydew Working Group continues to meet periodically at the Faserinstitut, Bremen, Germany.

The extensive review by Hector and Hodkinson (1989) brought together the existing information on the sticky cotton problem worldwide. The authors’ excellent treatment of the subject identified the scope and causes of the problem, methods for identifying lint sugars and cotton stickiness, and the available methods for dealing with the problem (blending, ginning additives, storage, washing, and the status of using microorganisms to break down sugars on lint to nonsticky components). The review confirmed that there are many sources of lint contamination that may cause lint processing machinery to malfunction. However, the major cause worldwide was identified as the sugar-containing honeydew excretions of phloem-feeding insects.

The sweetpotato whitefly outbreaks on cotton in the 1980s and the 1990s in the United States caused sticky cotton problems in California, Arizona, and Texas (Henneberry et al. 1998). Between 1994 and 1998, cotton growers in these states spent over \$153 million for sweetpotato whitefly control to prevent or reduce cotton lint stickiness (Ellsworth et al. 1999). The cotton industry and the scientific community responded with increased efforts to define the problem and provide solutions that were economically and environmentally acceptable. In this volume we review the most current information on sticky cotton as a supplement to the reviews mentioned earlier.

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## Chapter 2

### Scope and Economic Effects of Sticky Cotton

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#### Sticky Cotton, a Worldwide Problem

Upland cotton is the largest natural fiber crop in the world, as measured in hectares planted annually, metric tons of fiber produced, and the commercial value of the commodity. Cotton is grown on six continents and in more than 70 countries. Use of cotton is ubiquitous in the global textile industry.

Clean cotton lint, generally up to 7 percent moisture, will glide smoothly over metallic surfaces. Therefore, cotton lint that adheres to moving metal surfaces is likely contaminated with some type of adulterant. The effect of such adhesion is commonly called “stickiness,” and the contaminated lint is called “sticky cotton.” The term “stickiness” has a technical definition when it occurs in textile machinery: “the tendency of cotton fibers to stick to textile working surfaces” (European Committee for Standardization 2001). Therefore, measures of cotton stickiness are direct or indirect measures of contaminants and their purpose is to quantify the potential stickiness of the fiber when passed through textile machinery (European Committee for Standardization 2001). Occasionally in severe cases, stickiness may occur in cotton harvesting equipment, such as the spindles of mechanical cotton pickers, or in ginning, such as at gin stands or lint cleaners. At the spinning mill, stickiness may occur at pressure points in cards and creel drives, drafting zones of drawing and roving frames, and in combers and spinning frames.

Cotton stickiness is a worldwide problem, both from the perspective of fiber processing and from the perspective of cotton production (Hector and Hodkinson 1989, Perkins 1993, Gourlot and Frydrych 2001, Strolz 2001). Moreover, the problem increased during the early 1990’s (Perkins 1993, Strolz 2001). In 1995, an International Textile Manufacturers’ Federation survey suggested that as many as 20 percent of all individual types of cotton (called descriptions in the survey) might be sticky (ITMF 1995).

While not all cotton-producing areas are heavily affected by stickiness, and not all areas that are affected have notable stickiness problems every year, a large number of countries are sporadically to chronically affected, and some countries have been dealing with stickiness as a chronic problem for 20 years or more (ITMF 1989, 1991, 1993, 1995, 1997, 1999, 2001, Hector and Hodkinson 1989, Strolz 2001). In general, cotton produced in arid regions is more likely to be affected than is cotton grown in areas with more rainfall. This is because rainfall between boll opening and harvesting can remove water-soluble contaminants, disperse the contaminants enough to alleviate sticky points, or both.

#### Sources of Stickiness

Ginned cotton lint may contain various field contaminants, including stem and leaf fragments, small pieces of cotton or weed seed, dust, and various contaminants that may include fragments of cloth, plastic, or metal (ITMF 1989, 1991, 1993, 1995, 1997, 1999, 2001; see also chapters 3 and 4). Grease, oil, or seed fragments, as well as naturally occurring sugars, when in excess, can cause tagging or tufting of lint on moving machinery parts and the accumulation of lint or gummy residues on textile equipment. At harvest, cotton fibers typically contain less than 0.4 percent low-molecular-weight sugars (Perkins 1971; also see chapter 3). Particularly when a relatively high proportion of the ginned lint is comprised of immature bolls, the cotton may exhibit higher than normal and higher than desirable levels of monosaccharides and disaccharides (Wyatt 1976). Such immature cotton has not fully developed within the boll, typically has thin-walled fiber, and often measures less than 3.0 in micronaire (Institute of Textile Technology 1987). Cotton fiber containing greater than the normal range of reducing sugars may be difficult to process because of stickiness (Perkins 1971).

Physiological sugars such as glucose, fructose, and sucrose, in low concentrations, are normal constituents of mature cotton. The sugars most often causing problems in textile processing are from insect honeydews, because they are intrinsically stickier (Hector and Hodkinson 1989, Miller et al. 1994; also see chapter 4). The most frequent honeydew-producing insects are cotton aphids (chapter 6) and sweetpotato whiteflies (chapter 5).

## Effects of Stickiness on Growers, Ginners, Merchants, and Textile Mills

The presence of cotton aphids or sweetpotato whiteflies during the later part of the season suggest that insect honeydews may be deposited and under certain environmental conditions may persist through harvest at levels that could cause processing problems. Fieldmen may suspect stickiness from the appearance of the crop at or before harvest. The presence of sooty mold on open bolls indicates colonization by carbohydrate-consuming fungi, such as the common *Aspergillus* and *Penicillium* spp., and suggests the presence or previous presence of sugars that have been deposited on or exuded from the exposed lint. Fungi may actually consume a large fraction of the free sugars, and their presence may suggest a lowered potential for stickiness. However, cotton showing sooty molds will generally be discounted for color grade. Lightly contaminated fiber may not show problems during picking, where spindles are lubricated by water, or at ginning, where temperatures and moisture content are controlled to regulate output efficiency.

The point when stickiness is first detected as an operating difficulty depends on the type of contaminant and the level of contamination (table 1) (Ellsworth et al. 1999). Cotton that causes moderate problems at the mill may have caused little or no problem when saw ginned and may have been picked without difficulty. However, lint that shows buildup of sugars on picker spindles will very likely slow down ginning and may rapidly shut down a carding line. Unless lint contamination is extreme, stickiness usually is first found at the textile mill.

While upland cotton is predominantly saw-ginned, roller ginning is chiefly used for the longer staple Pima. (chapter 11). Pima cultivars may also be called Sea Island or Egyptian cottons depending on their pedigrees or area of production. Roller ginning may be affected adversely by stickiness from moderate levels of sugar, while saw-ginned cotton is less sensitive to moderate contamination. Thus, for saw-ginned cotton, stickiness is usually first detected at the textile mill (table 1).

Textile processing of fiber begins with opening and cleaning, aligning the fibers and further removing trash by carding, and then further aligning and blending the fibers in the form of a sliver on drawing frames. In textile mills, fibers are drawn against mechanical resistance. Difficulties caused by stickiness in textile

mills typically range from a buildup of gummy residues on cards or draw frames that may accumulate over periods from hours to a few days to rapid lapping of card webs that may occur within much less than an hour of running cotton that is heavily contaminated with insect honeydews. The time for obligatory cleaning, or shutdowns, in the processing of a lay-down, depends on the types and amounts of contaminants (chapter 14). The higher the level of contamination, the more likely that mechanical problems will be encountered at earlier stages in the processing.

Despite extensive efforts over the last two decades to develop and evaluate testing methods and coordinate standards there is no recognized commercial standard for measuring sticky contaminants in cotton lint (Fadlalla et al. 2002; also see chapter 13). Many European and Asian mills purchase large portions of their cotton from African and Asian countries where stickiness is a sporadic to endemic problem. Some of these mills have incorporated screening equipment using in-house quality control procedures or have special operations to decontaminate sticky cotton by washing or treating sugar-contaminated cotton with enzymes (Dean Pelczar, 2003, personal communication). Since U.S. production has been relatively free of sticky cotton, few such quality-control procedures are in place in the United States, nor are such preventive measures commonly employed in textile mills in Latin America or East Asia, areas that are major importers of U.S. cotton.

Given the general lack of quality-control surveillance, stickiness often is first detected by the mill as an unwelcome experience. All parties that have a financial stake in the cotton from production through fiber processing are adversely affected, including growers, ginners, cotton merchants, and textile mill owners. Parties are affected to different degrees, and by different mechanisms. At the gin, stickiness can reduce lint output, generally measured in bales per hour (Perkins 1993). At the textile mill, stickiness in purchased inventory causes multiple problems. Stickiness reduces processing efficiency and may reduce yarn quality. Typically, a mill that has received sticky cotton will complain to the offending procurement sources, usually a cotton merchant or gin, and request or demand a contract adjustment. The mill will lose income to decreased processing efficiency and may lose additional income from discounts on off-quality yarn. The supplier of the sticky cotton may lose

income to contract rebates and may lose future sales because of loss of reputation as a reliable supplier. In fact, other suppliers from the same region may also lose their reputations as quality suppliers because of the association of stickiness with the region. Since there is no system for pretesting cotton for stickiness, and much cotton is sold in advance of harvest, producers from the region tend to lose future income by price discounting in the year or years following a stickiness episode (Ellsworth et al. 1999).

## Responses to Stickiness

As described in figure 1, it is about 3 months after sticky cotton is harvested before the mills realize it is sticky. Although mills can respond to stickiness in different ways, they all require additional processing costs. One strategy is blending sticky cotton with nonsticky cotton. Once mills encounter stickiness problems with bales from a particular source, they will likely purchase additional cotton from other sources in order to blend and meet the supply shortfall caused by unknowingly purchasing sticky cotton. Mills may have to pay higher prices for the nonsticky cotton used for blending. Even if they don't have to pay a higher price for securing cotton to replace the sticky cotton, storage and sorting costs will be higher. Another strategy is to slow processing and output rates (kilograms of yarn per hour), which increases operation time and the cost per unit of yarn. Mills may also add labor to monitor and clean machinery. Without any renegotiation of price paid for quality received, mills will bear all of the higher costs associated with processing sticky cotton on purchases they have made in advance of processing this cotton.

After mills realize cotton is sticky from a region for a crop year or can be sticky from a region, they will avoid the region in securing future supplies or only purchase cotton from the region at a discount. Expected additional processing costs reduce buyers' willingness to pay for cotton from regions with a reputation for stickiness. A reputation for stickiness is likely to exist until several years of nonsticky cotton production can rebuild the reputation for quality from a region. The next section provides a conceptual framework for how stickiness affects producers and ginners from the sticky cotton region plus mills that purchase lint from this region.

## Economic Effects of Stickiness on Mills and Cotton Producers

The economic consequences of stickiness can be examined in two critical stages. In the first, mills unknowingly purchase ginned cotton that they later discover is sticky. In the second stage, mills come to suspect that cotton from a particular region may be sticky and adjust their cotton purchasing decisions accordingly. In the first stage, the mills primarily bear the costs of stickiness, while in the second, costs are passed back to growers in the source region.

To illustrate, first consider the problem of an individual mill (or group of mills in a region). Figure 2 illustrates baseline mill production decisions and returns. The mill is a price-taker; that is, given competition, it takes the market price of cloth,  $P^c$ , as given. The mill's supply (or marginal cost) curve,  $S$ , shows the cost of producing one additional unit of cloth. This cost curve accounts for the cost both of purchasing ginned cotton and of processing it. The mill maximizes returns where its marginal cost equals the price of cloth, producing  $Q$  units of cloth. Gross sales equal  $P^c \times Q$ , while total costs equal the area under the supply curve,  $(c)$ . Net returns, then, equal the difference, shown as triangle  $(a)$ . The demand for ginned cotton from mills for a given region is highly elastic. That is, given quality and all other factors as equal, mills will be very responsive to securing most (none) of their cotton bales from the region with the lowest (highest) price.

Now consider the case in which the mill unknowingly purchases some sticky cotton from a particular source. Initially, the occurrence of sticky cotton at the textile mill does not affect the price producers receive or the quantity of raw cotton purchased from the region because mills did not anticipate that such cotton would be more expensive to process. Recall that in the timeline given in figure 1, the lag between a producer selling seed cotton and this cotton reaching the mill for processing is at least 2 to 3 months. Thus, there is a 2- to 3-month period of spot sales, plus any forward-priced sales, during which producers from the sticky region are not assessed a price discount.

Stickiness affects the mill, however. Figure 3 illustrates the case where a mill unknowingly receives sticky cotton from a region. Because of stickiness, the mill incurs higher processing costs. The mill's supply (marginal cost) curve shifts up from  $S$  to  $S'$ . Because the mills that receive and process sticky cotton into



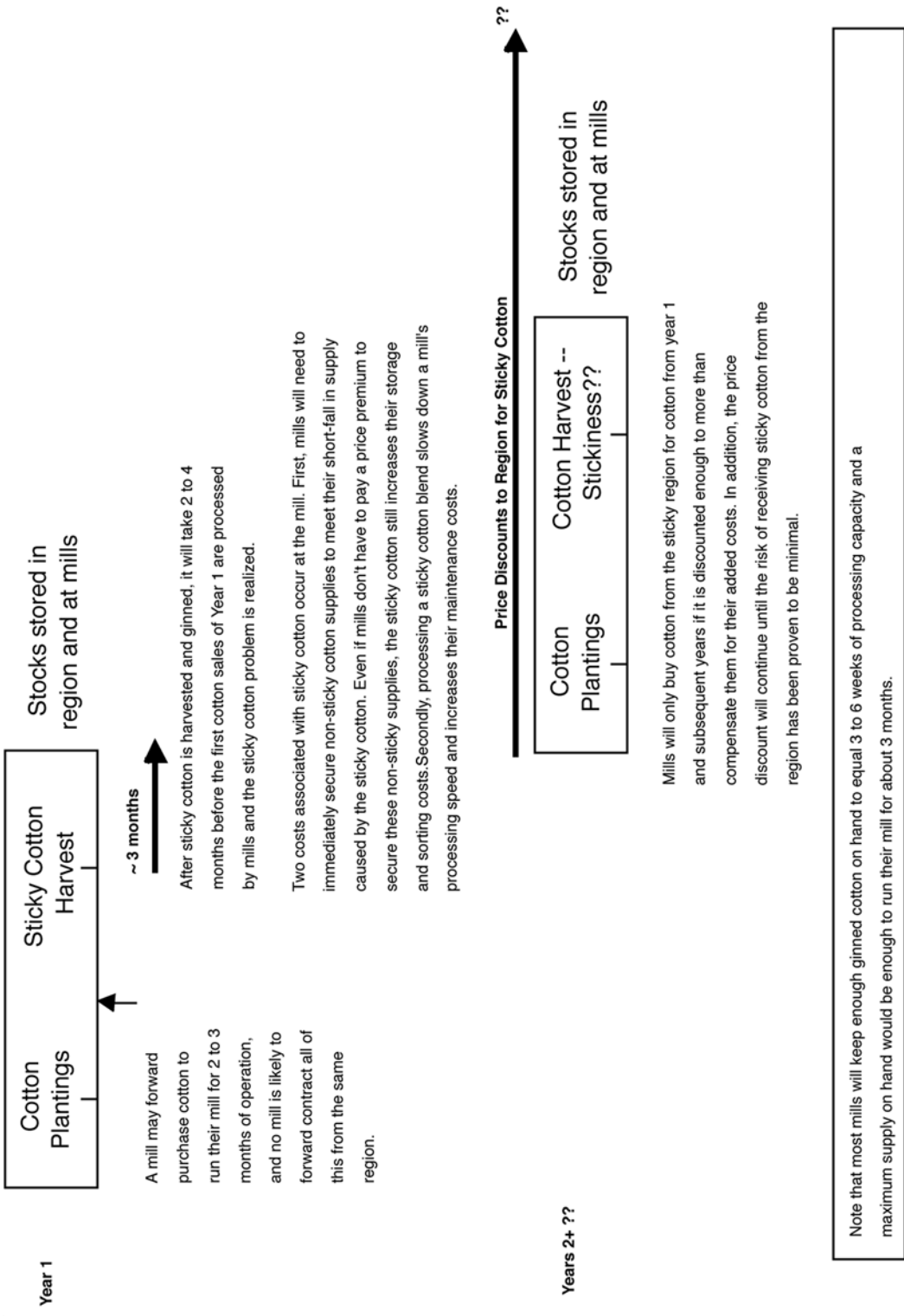


Figure 1. Timeline of sticky cotton production and mill purchasing.

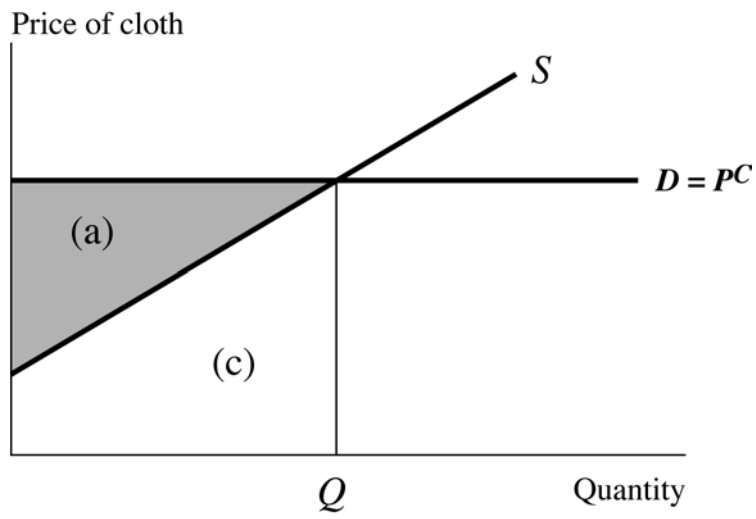


Figure 2. Textile supply, demand, and returns: baseline case.

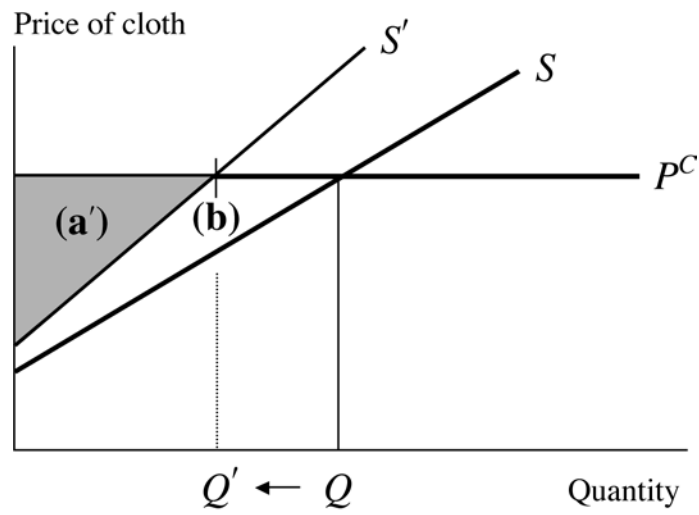


Figure 3. Effect on mill of unanticipated purchase of sticky cotton.

cloth need to be price-competitive with other mills, they are unable to pass on their cost increase or receive a higher price for their cloth than the market price of  $P^C$ . The mill is able to process less total cloth relative to a “no-sticky-cotton” case. Mill output is reduced from  $Q$  to  $Q'$ . Compared to figure 2, net returns fall from (a) to (a') and the loss to the mill from stickiness is represented by area (b). The increase in a mill's cost structure (shift of  $S$ ) and economic loss, (b), will increase with the percentage of sticky cotton it inadvertently purchased and the extent of the stickiness.

In the following year, the mill will expect to earn area (a) in figure 2 if it purchases nonsticky cotton. The mill will alter its purchasing to avoid buying cotton from sticky sources and avoid expected stickiness costs, (b) in figure 3. Mills will only purchase cotton from a suspected source of stickiness if the purchase price of ginned cotton is discounted *at least* as much as the expected additional cost of processing the sticky cotton. If mill purchasers are risk-averse, the discount required to induce them to purchase potentially sticky cotton will be even higher than expected additional costs, reflecting a risk premium.

Because mills do not know the stickiness of individual bales or shipments, they form expectations of stickiness based on experience with regions where they purchased cotton. If a region has been identified as a supplier of sticky cotton in the recent past, mills may require discounts on all cotton from that region or avoid cotton from that region altogether.

Figure 4 illustrates the effect of a reputation for stickiness on grower returns. Under normal (nonsticky-cotton) conditions, growers may expect to sell as much cotton as they want in a primary market at a given competitive farm price  $P^F$ . A secondary outlet may exist, such as an export market or forfeiture on government loans, where cotton may be sold at a lower price. This secondary outlet, however, pays a lower price,  $P^S$ . Under normal conditions, producers will not sell in this market. Given the expected price,  $P^F$ , growers produce  $Q^e$  bales of cotton.

Once the cotton is harvested, however, growers essentially have a vertical supply curve,  $Q^h$ . If their region has gained a reputation for stickiness, growers will find that they can not sell the full quantity  $Q^e$  at the expected price,  $P^F$ . Rather, different purchasers, based on previous experience and expectation of stickiness problems, may require differing levels of discount before they will purchase any cotton. The actual price schedule growers face is now  $P'$  illustrating that cotton cannot be sold to the primary market without discounts. At the limit, discounts required to sell the cotton may be large enough that a certain portion of the cotton crop goes to the secondary market, either a less attractive export market or to government forfeiture. In figure 4, the amount of cotton going to the secondary outlet is  $Q^e - Q'$  bales. The gray shaded area illustrates the loss to growers in the region resulting from price discounts. Discounts may last for multiple years as long as a region has a reputation for stickiness.

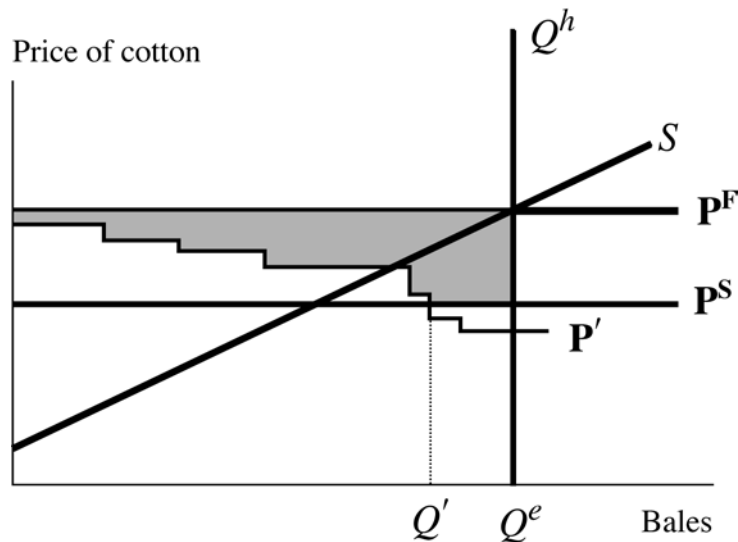


Figure 4. Effect of stickiness reputation on grower returns.

Together, figures 3 and 4 show how the distribution of costs of stickiness are incurred and shift over time. When mills make unanticipated purchases of sticky cotton, it is they who bear most of the cost of stickiness. Once a region develops a reputation for stickiness, however, competitive pressures cause the costs of stickiness to be passed back to growers in that region.

## Quantifying the Costs of Stickiness

### Effect of Stickiness on Mill Processing Costs

The previous discussion uses economic theory to describe the transfer of the costs of stickiness from mills to ginners and producers; although, as will be further discussed, there is a lag in the transfer. How much does stickiness cost? Despite the attention stickiness receives, little formal analysis has been done to quantify the costs that stickiness inflicts. Most quoted costs are anecdotal. Floeck and Ethridge (1998) note, “While some knowledge exists about prevention, measurement and treatment, there is no information about economic losses from sticky cotton. That is, the costs incurred by textile mills due to sticky cotton have not been quantified.”

To our knowledge, there has been only one study that has attempted to quantify costs of processing sticky cotton. Results are summarized in Floeck and Ethridge (1997, 1998). The study was based on a survey of nine textile mills dealing with sticky cotton from the 1995 West Texas crop. In that year, a number of factors contributed to high levels of stickiness in West Texas cotton. Eight of the nine mills experienced stickiness, with seven of those eight using blending to deal with it, six slowing processing, and four adding workers. Floeck and Ethridge found that the weighted-average cost of blending sticky cotton at the textile mill was approximately 3.5 ¢/lb (7.7 ¢/kg) over a range of stickiness levels. Blending costs ranged from 2.5 ¢/lb (5.5 ¢/kg) for very low stickiness to 3.9 ¢/lb (8.6 ¢/kg) for high levels of stickiness. However, this estimate was based on cost-of-production data from only one mill. Added labor costs (estimated from two mills) averaged \$20.00 per hour for both low and high levels of stickiness.

### Effect of Stickiness on Price of Cotton

A later study by Hoelscher and Ethridge (1998) attempted to quantify how much the perception of stickiness affected the price of the 1995 West Texas crop sold in the 1996/97 market. They found that 1995

crop cotton (sold in 1996), with the same high volume instrument (HVI) quality attributes, received an average discount of 2.86 ¢/lb (6.31 ¢/kg) below the 1996 crop. This difference fluctuated between a 8.6 ¢/lb (19.0 ¢/kg) discount and a 1.6 ¢/lb (3.5 ¢/kg) premium, but premiums were paid only four times throughout the year. In later periods, discounts remained primarily between 2 and 4 ¢/lb (4 and 9 ¢/kg). The simple price-effect model predicts that discounts for stickiness will be demanded with a lag and that price discounts growers must give will be roughly equal to mills’ increased processing costs. Although based on limited data, the stickiness cost estimates from Floeck and Ethridge (1997, 1998) are quite close to the price discounts reported in Hoelscher and Ethridge, as theory would predict. These figures are also consistent with the 3 to 5 ¢/lb (7 to 11 ¢/kg) price reductions observed for Arizona cotton compared to California cotton with the same HVI attributes after severe whitefly infestations in 1992 and 1995 (Ellsworth et al. 1999).

### Averting Costs as a Measure of the Cost of Stickiness

Expenditures to control pests that can cause stickiness provide an indirect measure of the cost of stickiness to producers. To measure the costs of environmental damages, economists sometimes look at *averting costs* or *defensive expenditures*—expenditures made to avoid or avert a problem (Cropper and Freeman 1991, Smith 1991). Defensive expenditures tend to understate the true cost of damages because people would not knowingly pay more to avoid damage than the cost of the damage itself. In principle then, expenditures to control stickiness could serve as a conservative measure of its cost to producers. Tables 2 and 3 show U.S. expenditures to control cotton aphids and sweetpotato whiteflies. U.S. producers spent over \$0.5 billion to control aphids between 1989 and 2001, or about \$7.59 per hectare on average. Arizona and California spent over \$220 million to control whiteflies between 1992 and 2001, and Arizona spent over \$58 million, or almost \$160 per hectare, in 1995. Pest control costs, however, are an upwardly biased measure of the costs of averting stickiness. This is because producers spray for these pests both to avert stickiness and to avert yield losses. The values in tables 2 and 3, then, overstate expenditures made to avert stickiness alone.

In cases where stickiness costs are large relative to yield losses, however, pest control expenditures can provide a good approximation of averting costs.

Arizona may be one example of such a case. Figure 5 shows the ratio of pest control expenditures to the dollar value of yield losses for major cotton pests in the state. In other words, it is defensive expenditures divided by damages *not* avoided. It is not surprising that pest control expenditures exceed the value of actual damages. In such a case, pest control expenditures can still be much less than the cost of damages *avoided*. The figure shows that for most pests in most years, this ratio is less than two. Beginning in 1994, defensive expenditures to control whiteflies began to far exceed yield losses, by nine times or more in some years. For Arizona, it appears that some factor other than yield protection, such as averting stickiness, is motivating the relatively large expenditures on whitefly control.

### Market Perception of Stickiness Among Cotton-Producing Countries

Since there is no standard measure for stickiness, there is no possibility of conducting random sampling of the cotton to test for stickiness in international commerce. However, in alternate years the International Textile Manufacturers' Federation (ITMF) conducts a survey to estimate the contaminant levels found in internationally traded cotton. Since 1989, this survey has estimated the incidence of stickiness by questioning spinning mills regarding the country of origin and

name of the growths, called the “descriptions,” they have purchased, and the occurrence of stickiness in these various sources. The basic unit of the survey is the mill’s evaluation of the description as they have consumed it over the previous 12 months. An assumption needed to compare values of different origins is that no description has been consumed to a distorting degree—that is, consumed in such a large relative amount, compared to other descriptions, that there is a disproportionate probability of its being cited as exhibiting a particular contaminant. There is no guarantee that this assumption is valid, and it is probable that some mills do purchase disproportionately among international sources. Moreover, the specific inquiry is such that the data tend to cognitively magnify the apparent incidence of sticky cotton. The data are presented as the percentage of mills that have indicated stickiness during processing over the previous 12 months. In the survey, there is no provision to indicate the relative severity of the stickiness or the number of occurrences among the bales ascribed to the description. Theoretically, one bale in many thousand consumed could give a positive stickiness indication. Despite these limitations, the ITMF survey is a valuable tool because it is done with a consistent procedure. Given a relatively large number of respondents, and there are generally 200 to 300, the

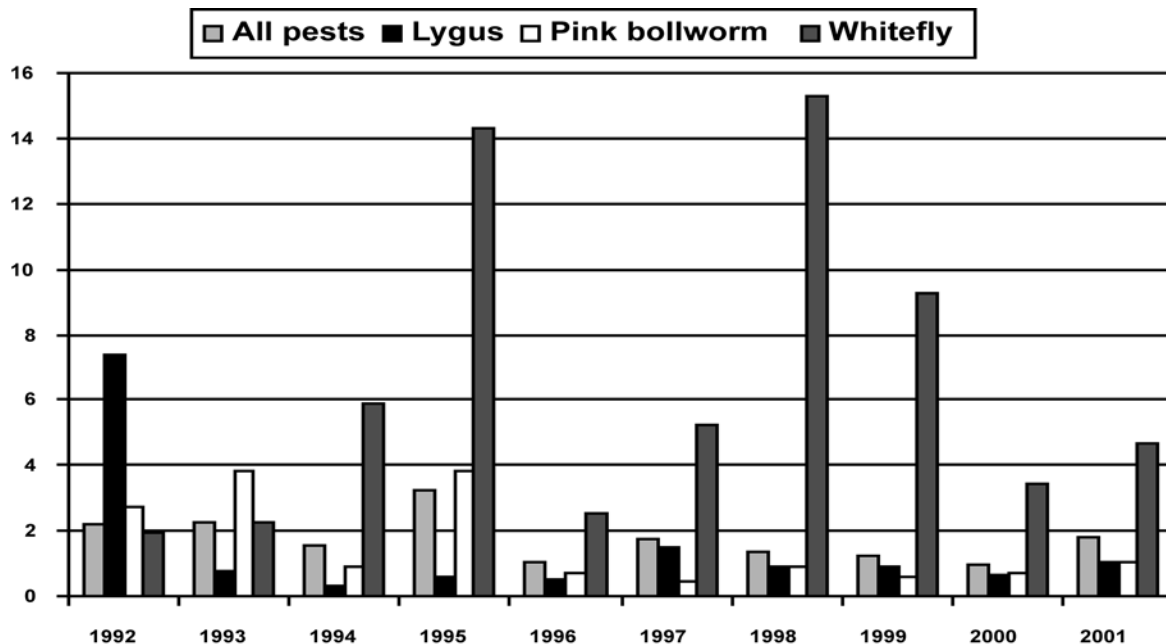


Figure 5. Ratio of control costs to value of yield losses in Arizona cotton.

responses should give relative indications of trends among years and among sources.

Although complaints of stickiness are reported to some extent from essentially all descriptions in all surveys, the highest occurrence is associated with African sources (figure 6). Sudan has experienced a severe and chronic problem with stickiness since the 1970s, and will be further discussed as a case study below. In addition, Francophone Africa has experienced problems with stickiness resulting from both aphids and whiteflies. Nine Francophone African countries produce and export cotton. The Common Fund for Commodities, through the International Cotton Advisory Committee and CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) has undertaken extensive research efforts to reduce the effect of stickiness on prices of cotton produced in Sudan (Gourlot and Frydrych 2001). However, since reports of Francophone African cotton prices aggregate all national sources into a single quotation, it is difficult to relate market perception of stickiness in Francophone Africa to price effects, because the countries from this region experience stickiness to different degrees.

U.S. cottons constitute a large fraction of all internationally traded cotton. Therefore, U.S. descriptions are more likely to be cited for contaminants than countries or regions with smaller exports because of U.S. cotton's greater exposure from its higher commercial volume. Certain U.S. descriptions, chiefly from the western states, have been indicated as exhibiting stickiness in certain years (figure 7). Considering years from 1989 to 2001, the mean incidence of stickiness is perceived as essentially equal for Texas, Arizona, and California, the principal irrigated production areas in the United States. However, the sources of stickiness differ and the relative incidence of stickiness has varied among these regions over the reporting period. For the western states, mill perception of stickiness, as reported by the ITMF survey, differs from incidence as understood by local producers, researchers, and ginners. In particular, perception of stickiness appears to increase in years following a stickiness outbreak whether field conditions indicate favorable conditions for stickiness or not. It seems likely that such dynamics of market perception affect other cotton-producing regions as well.

In the early 1990s, there was perception of stickiness associated with Arizona cotton. This period coincided

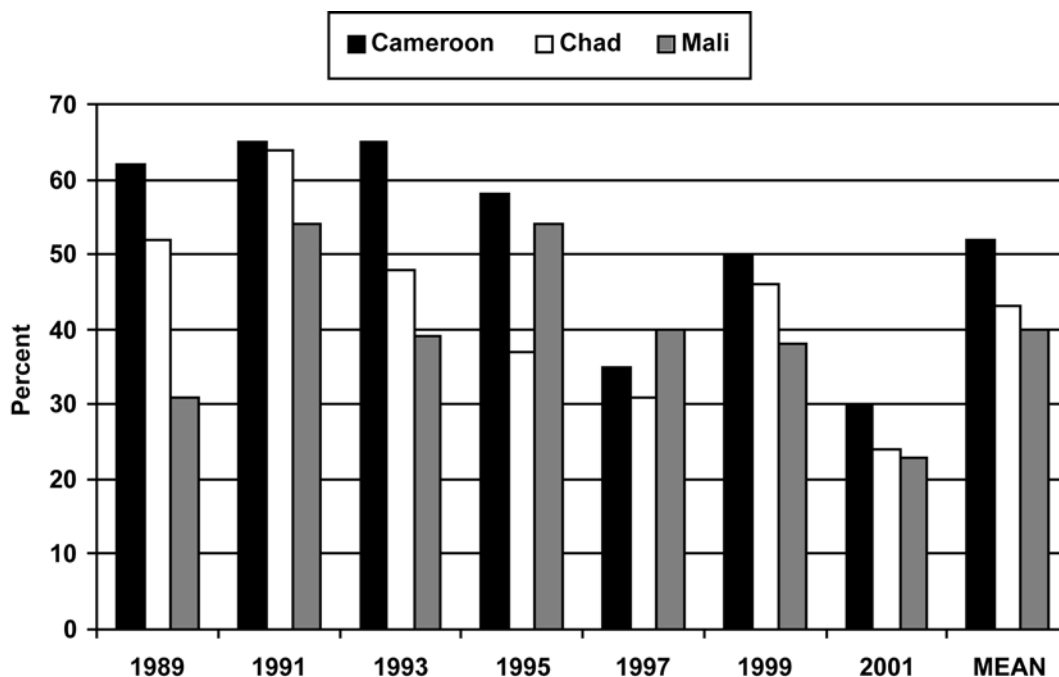


Figure 6. Summary of International Textile Manufacturers' Federation survey of mills reporting at least one occurrence of stickiness in selected African growths.

with the rapid expansion of the sweetpotato whitefly in the Southwest (see chapter 5). Since this time, an integrated management plan for sweetpotato whiteflies has been developed and widely adopted (Dennehy et al. 1996). Since the mid-1990s, whitefly control has dramatically improved in Arizona, and the market's perceived association of stickiness with the area has declined (figure 7). Sweetpotato whiteflies also were identified in the San Joaquin Valley of California in 1993, and by 1995 was a late-season management problem in the Valley. California also developed a management plan, patterned after that of Arizona, and effectively managed whiteflies during the 1990s (Goodell et al. 1999). However, cotton aphids are also difficult to manage and are a significant pest in San Joaquin Valley cotton. Although the market's perception of the stickiness potential of California cotton declined in the early 1990's, transitory increases were noted in the ITMF surveys for the years 1997 and 2001. Overall, 1995 was a particularly costly one for insect management throughout the United States

(Williams 1996). In 1995, insect management problems included a serious outbreak of aphids in the West Texas cotton crop. Significant portions of the West Texas crop exhibited problems suggesting high levels of physiological sugars, aphid honeydew, dust, or a combination of these factors. Consequently, in 1996, after most of the West Texas crop grown in 1995 had been consumed by mills, more than 60 percent of the mills that had purchased West Texas cotton reported that some of this cotton exhibited stickiness. Although West Texas has an average rainfall of less than 50 cm/year, field research strongly suggests that lint stickiness is a rare event, in part because the crop typically is rained on at least once before it is harvested (Hague 2000).

In general, U.S. cotton has little potential for stickiness, including cotton from the western production areas of West Texas, Arizona, and California, where little sticky cotton is produced in most years. However, the insect outbreaks of 1992 in Arizona, of 1995 in Texas, and of

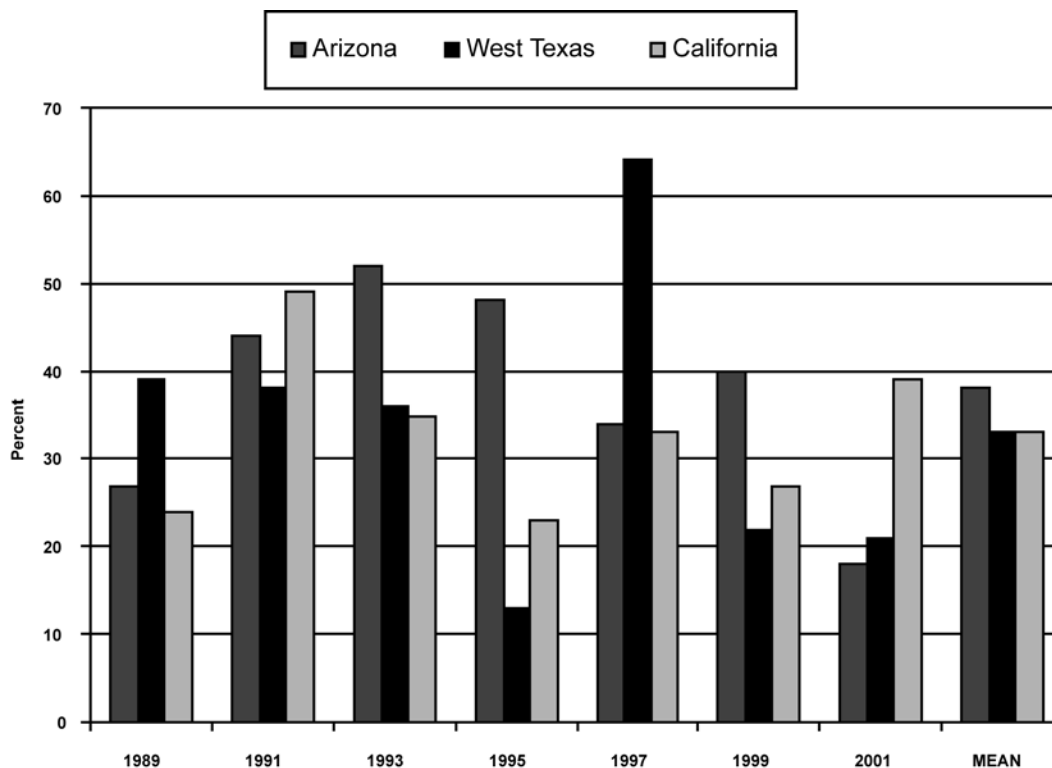


Figure 7. Summary of International Textile Manufacturers' Federation survey of mills reporting at least one occurrence of stickiness in selected North American growths.

1997 and 2001 in California show that stickiness for only one or two crop years likely prejudices the market for several years in the future.

### **A Production Region's Goodwill Value Can Be Damaged by Stickiness**

A supplier's reputation for producing quality goods is often referred to as the "goodwill value" or loyal customer patronage of a product. If all of a product's attributes could be observed prior to purchase, reputation or goodwill value would not be needed. Although HVI parameters provide mill buyers detailed information on many of cotton's quality attributes, stickiness is not measured. Because stickiness creates serious problems for fiber processors, stickiness is perceived by mill buyers as a very negative attribute. In effect, mill purchasers presume that the stickiness of high-quality cotton is zero. Therefore, sale of sticky cotton from a region is a serious breach of the customer's quality expectations and will result in a loss of goodwill value.

Almost all purchases involve some element of expectation concerning future performance or durability. Therefore, producers strategize concerning the type of product quality they want to project. A firm or industry's decision to produce a high-quality product is a dynamic one. The decision to target the high-quality segment of the market requires an investment period when the firm or industry is selling its product at less than the prevailing, high-quality market price. During this period, the product is proving its worthiness to the buyers. The industry hopes that buyers will eventually recognize the goodwill value of the product's quality attributes (Shapiro 1983). Because cotton is not traced or associated with individual farms, mills identify nonmeasured quality attributes like stickiness according to how cotton performs from a region rather than an individual farm. Thus, the collective reputation of a region of cotton production depends on all of the individual farmers' decisions. Using a theoretical framework, Tirole (1996) formally showed that individual reputations are determined by collective reputations, and vice versa. In addition, Tirole's analysis demonstrates that several purchasing periods are needed to re-establish a group's reputation for good quality following a one-time delivery of poor quality. This analysis demonstrates that while collective reputations can be rebuilt, maintaining a good reputation is easier than rebuilding it.

The following national case studies illustrate the effect on production costs, lint stickiness, and market reactions of selected outbreaks of honeydew-producing insects, in instances where such effects have been documented. Clearly there have been more cases than those described here. Understandably, documentation is lacking in many instances. Because goodwill value can be compromised, there is no advantage to communicating about the incidence of stickiness. In fact, there may be an advantage to not communicating it.

## **Case Studies**

### **Sudan**

Agricultural production remains Sudan's most important sector, employing 80 percent of the work force and contributing 43 percent of the gross domestic product (CIA 2002). Cotton has long been the country's main export commodity (Castle 1999) and as recently as 1991 accounted for 78 percent of Sudan's export earnings (World Bank Group 2002). Until the 1970s, sweetpotato whiteflies had been a secondary pest of Sudanese cotton. From that time to the present, it has been the primary cotton pest in Sudan (Dittrich et al. 1986). During 1965-75, pest control costs averaged 14.5 percent of total production costs. By the 1985/86 season, however, pest control costs rose to one-third of total production costs (Stam et al. 1994). From 1985/86 to 1989/90, Sudanese cotton area declined 44 percent (Castle 1999). Despite a period of rebound in the early 1980s, Sudanese cotton production has been trending downward since 1970 (figure 8). With the decline in cotton production and beginning of oil exportation, cotton now accounts for less than 5 percent of Sudan's export earnings.

Sudanese Acala cotton represents about 80 percent of Sudanese cotton production (Gourlot and Frydrych 2001) and has had a long-standing international reputation for stickiness. Respondents to ITMF surveys purchasing Sudanese Acala have consistently reported stickiness problems (figure 6). Between 1989 and 2001, the percentage of ITMF survey respondents encountering stickiness ranged from a low of 75 percent in 1995 to a high of 100 percent in 2001. For comparison, the survey grand averages over this period ranged between 18 percent and 27 percent. In selected African Franc Zone countries, reported stickiness problems have been trending downward since 1991, falling below 30 percent (figure 6).



In Sudan, much of the production is roller-ginned; therefore, stickiness problems are also encountered at the ginning stage. According to Gourlot and Frydrych (2001), in some cotton arriving at Sudanese mills, stickiness is “detectable with the naked eye.” Carlson and Mohamed (1986) assessed the effects of stickiness on gin efficiency through interviews of cotton classifiers and gin managers. They found that gins had to pay workers bonuses equal to 20 percent of base wages to replace ginning blades more frequently and that gins had reduced output per day. Khalifa and Gameel (1982) reported that stickiness causes reduction in roller gin production by 4.5 to 6.8 kg (10 to 15 lb.) of lint per hour. Such a decrease is about 50 percent of the normal rate of ginning.

Several studies have commented on the negative effect of stickiness on Sudan’s cotton export levels and export prices (Khalifa and Gameel 1982, Carlson and Mohamed 1986, Afzal 2001, Gourlot and Frydrych 2001, Freud and Bachelier 2001). Carlson and Mohamed examined data from the Cotton Public Corporation (CPC) in Sudan tracking average sales prices by year, cotton type, and cotton grade. They concluded, however, that, “The available information on cotton prices by region for the past 6 years does not indicate a consistent price discount for level of honeydew. The market prices paid by regions reflect many factors besides the level of honeydew.”

They quote a CPC official’s estimate that nonsticky cotton would fetch a 10 percent price premium, but concede, “This 10 percent premium figure is only a guess of the actual willingness of cotton brokers to pay for the absence of honeydew.”

Khalifa and Gameel (1982) estimated a \$15 million loss in revenue from stickiness in 1982, while Afzal (2001) updates that figure to \$30 million for 2001 but does not explain how it was calculated. Total cotton export revenues in Sudan were \$65 million in 2001. Gourlot and Frydrych quote estimates of price discounts obtained from the Sudan Cotton Corporation (SCC): “The discount currently imposed on Sudanese cotton is deduced from market data and is estimated by SCC to be 7 to 12 percent of the selling price.”

Freud and Bachelier (2001) note that the discount level varies with supply and demand conditions, with discounts being heavier in periods of relatively abundant supplies. This makes intuitive sense, because mills can afford to be more selective if total cotton supplies are large relative to projected demands. They report a discount level of 0.3 franc/kg (French franc) when the cotton price was relatively high at 10 francs/kg, and a discount rate of 0.5 franc/kg on a relatively low cotton price of 7 francs/kg. This puts the discount in the range of 3 to 7 percent of farm value.

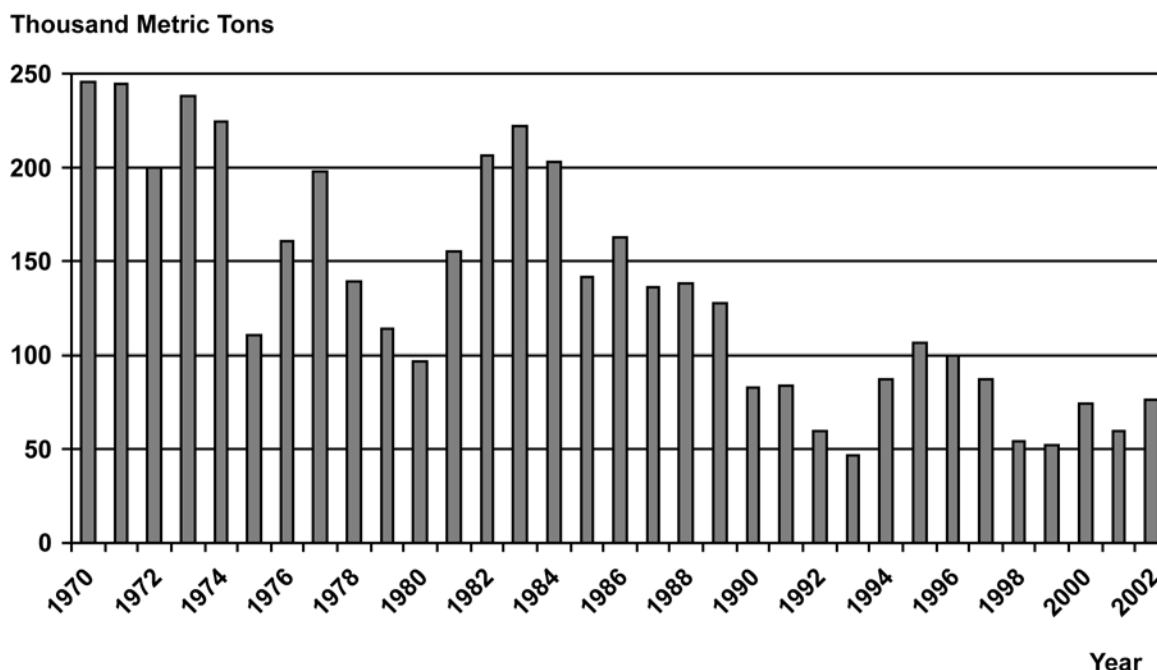


Figure 8. Cotton production in Sudan.

Different hypotheses have been put forward to explain the rise of whiteflies as a major cotton pest in Sudan. Eveleens (1983) posited that use of broad-spectrum insecticides disrupted the effectiveness of natural predators and parasitoids, leading to eventual pest control failures. Dittrich et al. (1986) argued that the major causes of the sweetpotato whitefly problem in Sudan were pesticide resistance and stimulation of fertility by DDT residues but also noted, “socioeconomic reasons and agricultural techniques may also have contributed.” In a reappraisal of sweetpotato whitefly infestations in Sudan, Castle (1999) developed a more complex explanation. While he also identified overuse of insecticides as a factor, Castle further emphasized the role of agricultural intensification and diversification, represented by increased cotton acreage, increased fertilizer use, later planting dates, and the rapid growth of secondary crops that also served as whitefly hosts.

### Pakistan

Cotton is one of Pakistan’s major export crops, although it has been increasingly consumed by a growing domestic textile manufacturing industry. Cotton’s share of total export revenues has fallen from 7 percent in 1991 to 1.5 percent in 2001. Growing sweetpotato whitefly infestations since 1989 have affected Pakistan’s cotton sector both through direct crop feeding, honeydew deposits on lint, and

transmission of cotton leaf curl virus (CLCV). CLCV affected nearly one million hectares of Pakistani cotton in 1992 and 1993 (Denholm and Horowitz 2002). Pakistan’s cotton production dropped precipitously from its historic high levels in 1991, falling 37 percent between 1991 and 1994 (figure 9). Denholm and Horowitz discuss the role of sweetpotato whitefly resistance to organophosphates and pyrethroids in contributing to pest control failures. However, Castle’s (1999) intensification thesis appears to fit the experience of Pakistan as well as Sudan. Between 1970 and 1990, cotton area grew 52 percent, cereals area grew 21 percent, irrigated area grew 31 percent, cotton yields doubled, and fertilizer use increased more than five-fold.

Pakistan’s whitefly problems do not appear to have translated into significantly large changes in purchaser’s perceptions of the stickiness potential of Pakistani cotton. In 1989 and 1991, ITMF survey respondents reported encountering stickiness in only 7 percent of descriptions from Pakistan. In 1993, this figure rose, but only modestly, to 10 percent, then to 11 percent in both 1995 and 1997, and to 22 percent in 1999. While the 2001 survey found that Pakistan’s descriptions were among the highest for overall contamination (particularly seed coat fragments), stickiness was not reported to be a problem.

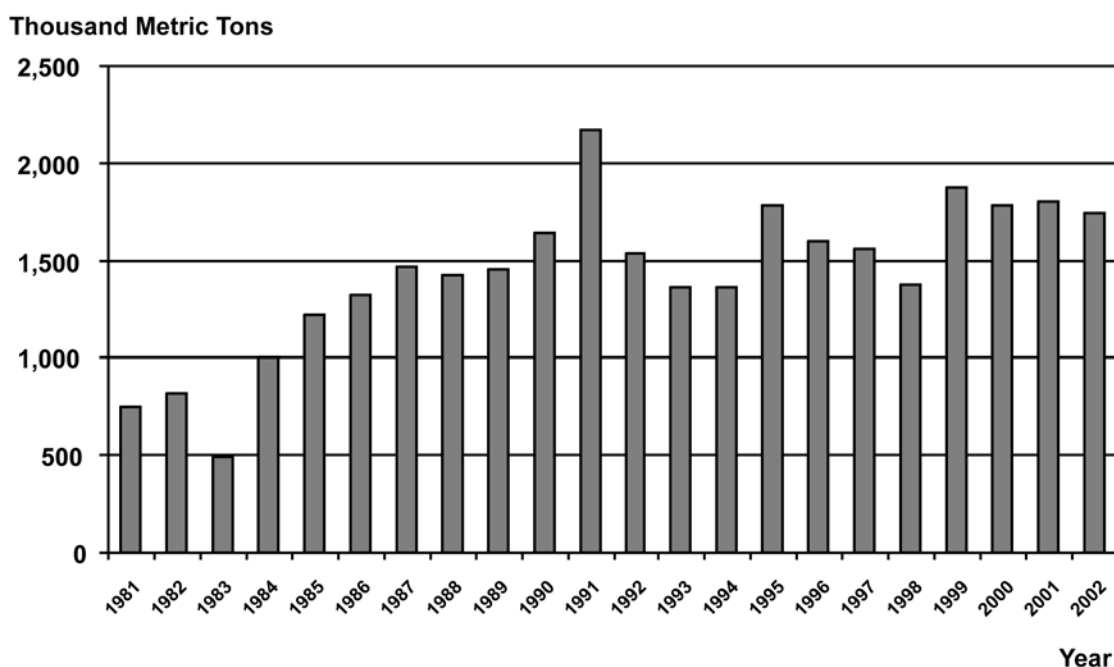


Figure 9. Cotton production in Pakistan.

Afzal (2001) has offered the number of pickings as an explanation for differences between Sudan's and Pakistan's incidence of stickiness. One picking is the rule in Sudan, whereas three or even four hand-pickings are customary in Pakistan. Afzal argues that multiple pickings deprive whiteflies of "the time to contaminate." The relative scarcity of labor in Sudan is one reason for the different picking rates. Vaissayre (2001) also notes that labor shortages in Sudan have led to late harvesting of cotton, which may also increase stickiness. Another factor could be the pattern of fall rains, or lack thereof. The longer cotton is left in the field, in general the greater the possibility that it will be rained on, therefore reducing the presence of sugars and the potential for stickiness.

### Arizona

Arizona's experience with cotton stickiness may be divided into three periods: first appearance of the sweetpotato whitefly as a significant local pest (1989-90), emergence of the sweetpotato whitefly as a major, pervasive pest (1991-95), and the most recent period of the whitefly as a manageable pest (1996-present). By 1991, it was well established in Yuma County

along the Colorado River, the major melon- and vegetable-producing area of the state, and had spread to central Arizona. By 1992, sweetpotato whiteflies were a problem throughout the state except for higher elevation counties (Ellsworth and Jones 2001).

Table 4 provides indicators of the emergence of sweetpotato whiteflies as a major cotton pest in Arizona in the early 1990's. In the middle period, 1992-95, the percentage of treated hectares, applications, control costs, and damage all grew sharply. Over this period, the costs of control and yield losses averaged \$48.2 million per year (in 1996 constant dollars). This is an understatement of total costs because it does not account for additional costs of price discounts based on perceptions of regional stickiness. Figure 10 illustrates that before 1992, Arizona cotton of grade 31-3 and staple 35 consistently received a price premium over the average U.S. price. After 1992, however, the price premium for Arizona cotton with these same HVI attributes has fallen below the average U.S. price and clearly dropped to an overall lower premium range. However, other factors, aside from perceptions of

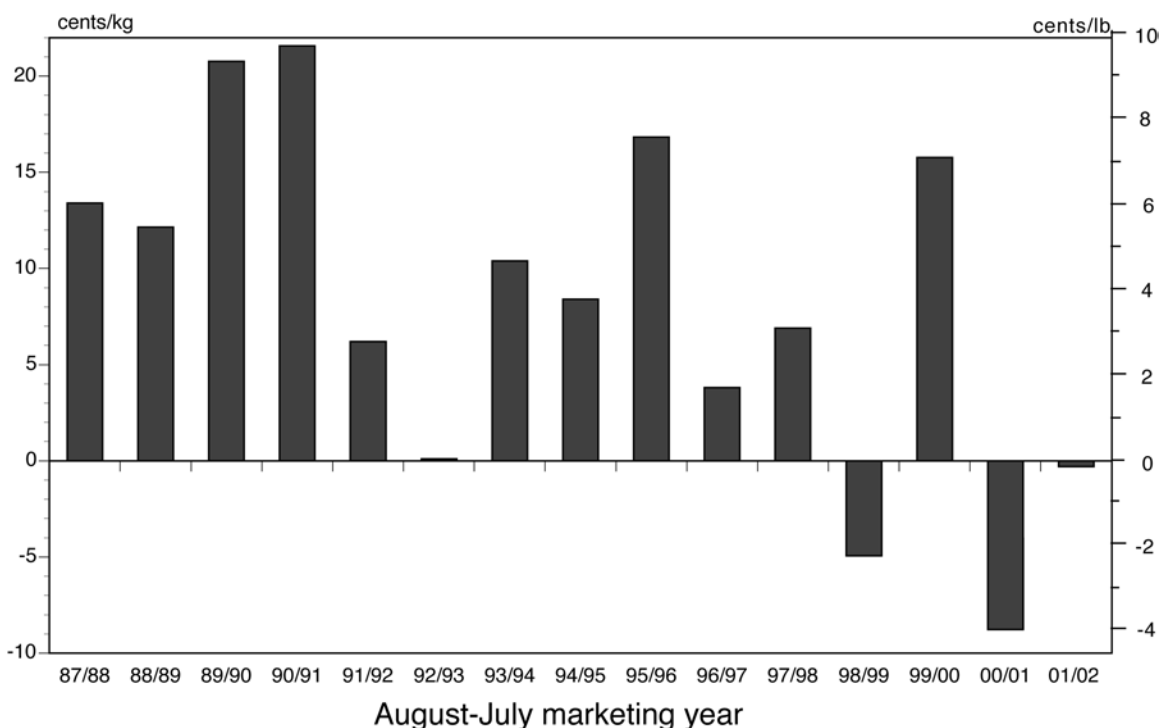


Figure 10. Difference in average price of Arizona cotton (31-3/35) compared to U.S. average price, 1987-2002. (Simple average of weekly 31-3/35 spot quotes [USDA/AMS 1987-2002] used to calculate monthly Arizona price. These prices were weighted by proportion of Arizona cotton marketings [USDA/NASS, 1988-2003] throughout the year to obtain marketing year average price.)

stickiness, can account for regional price differentials (Wade and Tronstad 1993). These factors include changes in regional demand because of West Coast exports to Asian countries and changes in micronaire levels. Although micronaire is held constant throughout figure 10 for Arizona, a large percentage of the crop having high micronaire increases the odds that a bale classed below the threshold for high micronaire could really be high micronaire. Increased logistical costs for blending high micronaire cotton also tends to depress regional prices for cotton that is not high micronaire.

Table 4 also illustrates the state’s success in bringing whiteflies under control in the late 1990s as whitefly control and damage indicators declined significantly since 1995. In the mid-1990s, the University of Arizona, the Arizona Cotton Growers Association, USDA, Cotton Incorporated, and private industry groups collaborated on aggressive programs to control whiteflies. The state obtained from the U.S. Environmental Protection Agency exemptions for use prior to registration of two novel insect growth regulators (IGRs), pyriproxyfen and buprofezin, which were rapidly adopted in 1996 (figure 11). Over 700 pest control advisors were trained and certified for proper use of IGRs as part of a mandated, grower-endorsed program (Ellsworth et al. 1997).

Community action plans were developed by the University of Arizona and the Cooperative Extension

Service and disseminated to grower groups (Ellsworth and Jones 2001). There was also recognition of the need for a multicommodity approach to whiteflies in the Southwest desert environment, where multiple and varied cropping patterns provided year-round hosts for the pest.

Buyer perceptions of stickiness mirrored the actual trends in whitefly damage and control costs (figure 12 and table 4). The proportion of respondents to the ITMF survey reporting stickiness problems with Arizona cotton rose to over 50 percent in 1993. This follows the worst year for whitefly yield damage in the state. Perceptions of stickiness have trended downward since then. As the state has gained control over whiteflies, reports of stickiness from Arizona cotton have reached their lowest level since 1989 and are no higher than the survey average.

Arizona’s experience demonstrates how quickly sweetpotato whiteflies can become a major economic problem to a region’s cotton producers. It also demonstrates that—

- community-based integrated pest management programs that include multicommodity considerations can effectively regain control over whiteflies and
- market perceptions of stickiness (or lack thereof) eventually respond to successful control.

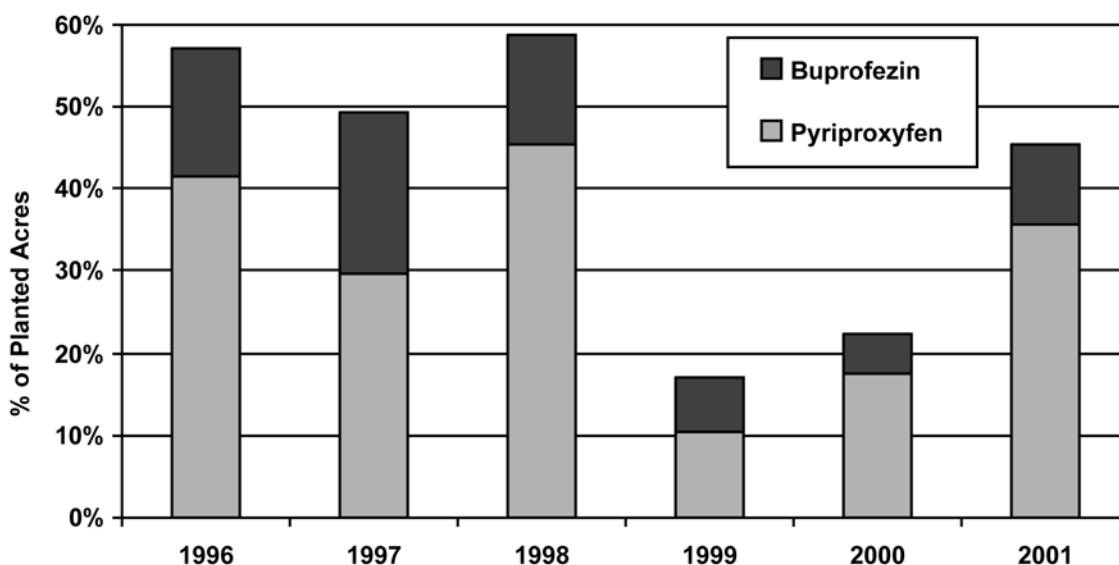


Figure 11. Percentage of Arizona cotton acreage treated with insect growth regulators.

## Texas

In 1995, several factors contributed to noticeable stickiness for 5 to 10 percent of the West Texas cotton crop (Hoelscher and Ethridge 1998). In early fall, heavy rains were followed by hot weather causing cotton regrowth. The new growth supported a late-season cotton aphid infestation. Growers did not use harvest aids to defoliate or desiccate the crop because of low yield potential. In addition, there was a lack of late-season rain that would have washed off some of the honeydew; and a killing freeze occurred later than normal, exacerbating these problems. The stickiness of the 1995 crop, while not detected or reported at gins, created several problems for mills (Floek and Ethridge 1997, 1998). By 1996, the 1995 West Texas crop had obtained a reputation for stickiness. In 1996, the 1995 crop was assessed discounts of up to 8 ¢/lb (17 ¢/kg) and on average was discounted nearly 3 ¢/lb (7 ¢/kg) compared to 1996 cotton with comparable (observable) quality attributes.

Figure 13 illustrates both how a reputation for stickiness lags stickiness events and how the reputation may persist after the event. This figure shows the

jump in aphid damage to the West Texas crop in 1995 that contributed to the stickiness event. Reports of stickiness appeared with a lag in the 1997 ITMF survey data. Since 1995, aphid damage has been minimal in West Texas, while reports of stickiness in the ITMF survey also have fallen, again with a lag. Hoeschler and Ethridge have shown how the reputation for stickiness carried into 1996. The ITMF survey data suggest that this reputation carried over into 1997 as well but had subsided by 1999. This suggests that a single stickiness event can have an effect on a region's reputation for 2 to 3 years.

## Mexico

Sweetpotato whitefly infestations in northwestern Mexico reduced cotton production in the region (Ellsworth and Martinez-Carrillo 2001, Oliveira et al. 2001). The Mexicali-San Luis Rural Development District, containing Mexicali, Baja California, San Luis Rio Colorado, Sonora, and surrounding areas, had been Mexico's largest cotton-producing district. In 1991 and 1992, severe whitefly infestations caused \$33 million in damage to cotton and other crops. In the Mexicali Valley, cotton production fell from 39,415

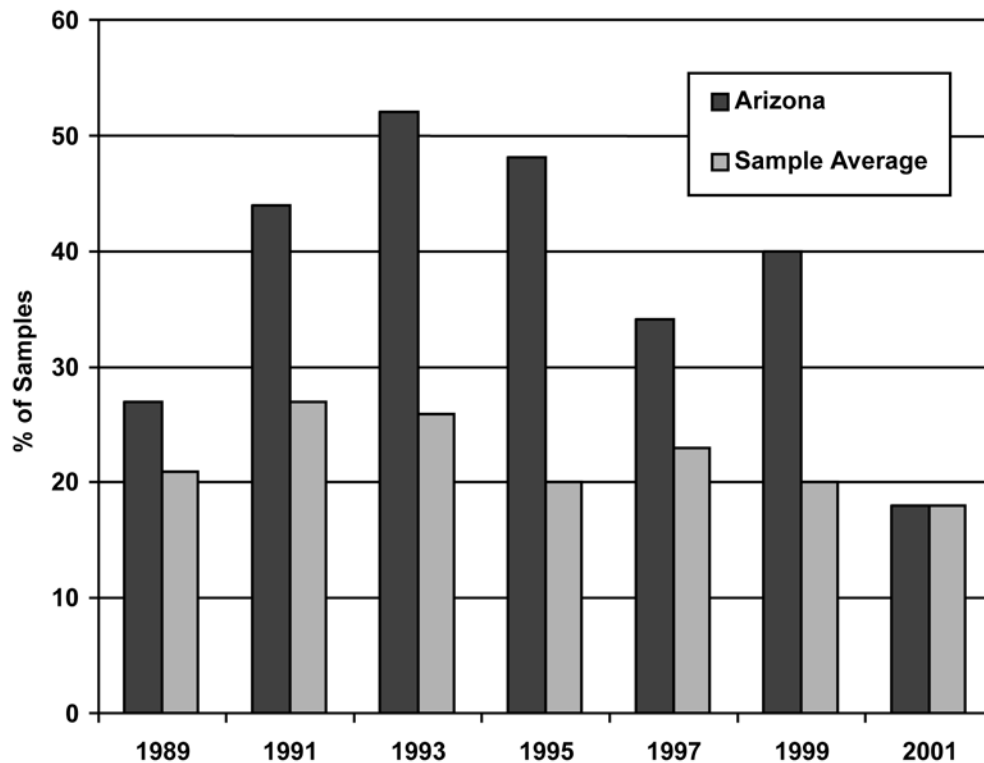


Figure 12. Percentage of samples for which ITMF survey respondents reported stickiness, Arizona and IMTF survey average.

hectares to just 653 hectares (Oliveira et al. 2001). Research identified soybeans (*Glycine max*) as the important host and recommended eliminating it from the local cropping system. However, between 1995 and 1996 cotton area fell by 65 percent in Sonora in response to further infestations. In Mexico as a whole, cotton acreage fell dramatically after the 1991 and 1995 seasons (figure 14). While other factors such as drought, changes in agrarian policies, formation of the North American Free Trade Association (NAFTA), and peso devaluation contributed to recent declines, stickiness problems were also important. In 1997, 21 percent of ITMF survey respondents reported encountering stickiness problems with Mexicali cotton. By 1999, this figure had risen to over 50 percent.

### Returns to Testing Cotton for Stickiness

A significant amount of research has been devoted to developing a commonly recognized system of testing and classifying cotton lint stickiness (chapter 13). Implementation of a testing and classifying system could help mills avoid unanticipated increases in

processing costs. It would also send price signals directly back to individual growers, increasing their incentives to prevent stickiness in the first place. At present, however, there is no generally recognized system for measuring stickiness that is compatible with the speed of commercial cotton classing. Along with technological constraints, there may be additional economic barriers to the adoption of grading systems for stickiness.

This section seeks to identify the costs and benefits to growers of a classification system for stickiness. It draws from Gourlot and Frydrych (2001) and Ahmed and Latif (2001). Their analyses focused on numerical applications drawn from specific conditions in Sudan. We will attempt to draw more general lessons about the conditions necessary for a testing system to be profitable to growers in a region as a whole.

Several key variables are needed to calculate the net benefits to growers in a particular region from a stickiness testing system:

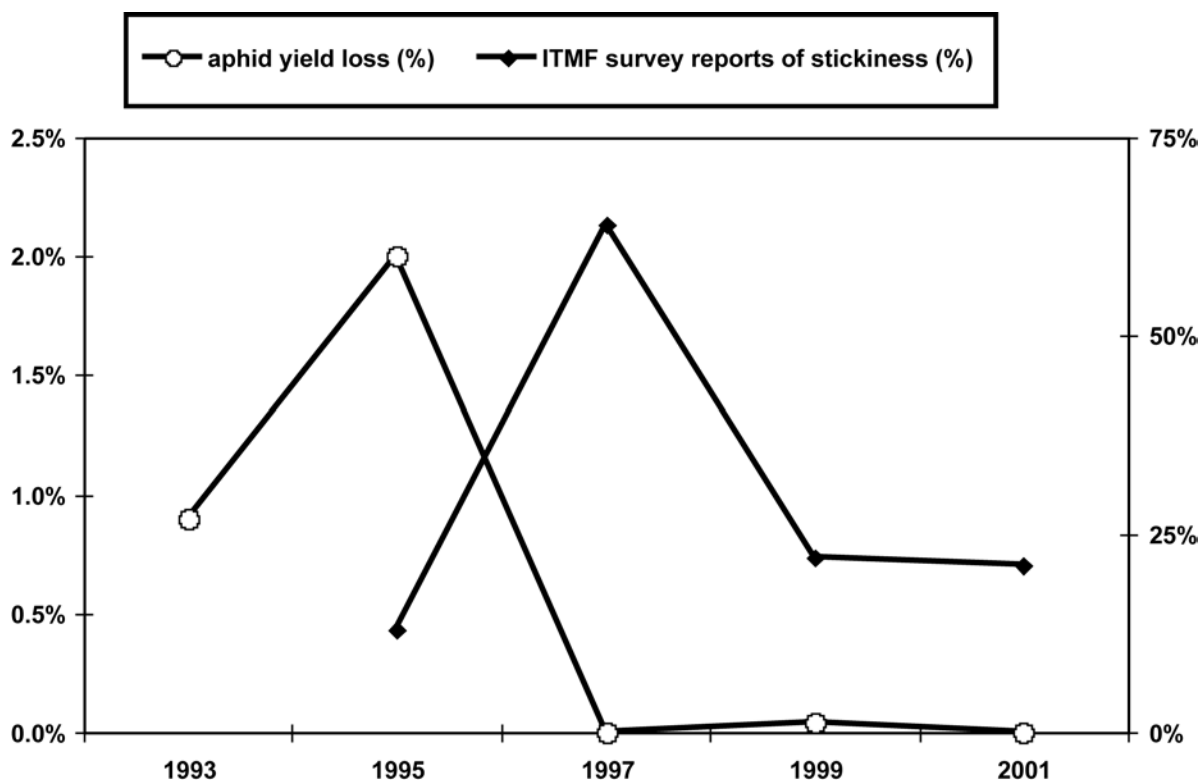


Figure 13. Aphid damage and reported stickiness in West Texas cotton.

- P base price per bale of cotton = price of cotton classed as nonsticky
- $d_0$  discount applied to cotton from region without grading system
- $P - d_0$  actual farm price received for cotton without grading system
- S proportion of cotton classified as sticky
- $d_s$  percentage discount applied to cotton classed as sticky
- C cost of testing and grading cotton

Consider a case where all producers in a region are penalized with a stickiness discount of  $d_0$  for cotton. If part of their cotton could be reliably tested and credibly certified as nonsticky, they could eliminate the discount  $d_0$  on all of their cotton certified as nonsticky. However, the cost of testing, C, would be passed back to them. In addition, they would face a discount of  $d_s$  for any cotton found to be sticky. Individual growers would benefit or lose from testing depending on what proportion of their crop was found to be sticky.

If the discount for stickiness is a constant percentage of base price, the net gain (per bale) of establishing a testing system for a region as a whole is G, where--

$$(1) \quad G = [P(1 - S) + (P - d_s)S - C] - (P - d_0)$$

This simplifies to:

$$(2) \quad G = (d_0 - C) - d_s \times S$$

Equation 2 suggests that in looking only at price effects, without considering any regional quantity effects, at a given incidence of stickiness (S), the net gain to growers from a region adopting a testing system--

- increases with the pretesting price discount (that is, in regions with a greater reputation for stickiness).
- increases as the cost of testing falls (through, for example, technological innovation).
- decreases with the size of the discount imposed on cotton found to be sticky.
- decreases as the percentage of sticky bales, S, increases.

Taking other factors as given, the net gains from testing are a (decreasing) function of the percentage of the crop that would be found sticky (figure 15). (The intercept of the line is  $d_0 - C$ , while the slope is  $-d_s$ ).

Beyond some critical, high incidence of stickiness (point  $S^+$ ), the gains from testing turn to losses. This critical level measures the scope for establishing a testing system. The critical incidence of stickiness,  $S^+$ , depends on market variables, where--

$$(3) \quad S^+ = (d_0 - C) / d_s$$

Equation 3 suggests that the critical incidence of stickiness--

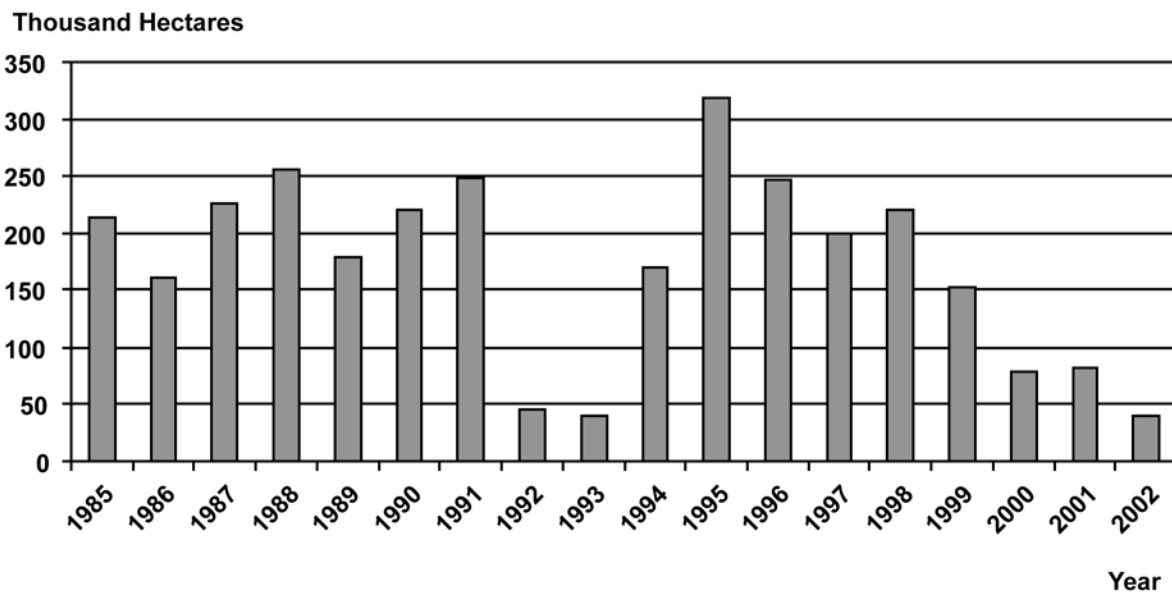


Figure 14. Cotton area harvested in Mexico.

- increases with a region's reputation for stickiness, represented by  $d_0$ .
- increases as the cost of testing declines (through technological innovation).
- decreases with the size of the discount imposed on cotton found to be sticky.

The first two changes cause the net gain line,  $G$ , to shift out (figure 16), increasing the scope for a testing system (that is, increasing  $S^+$ ).

Taken together, equations 2 and 3 provide some insights about the circumstances where a testing system would *not* be attractive. This will be in regions—

- with a "high" incidence of stickiness (above  $S^+$ ).
- without a reputation for stickiness and not facing stickiness discounts ( $d_0 = 0$  or close to 0).
- where buyers' perceptions of the incidence of stickiness are relatively accurate.

In the last case the pretesting discount  $d_0$  will be close to  $Sd_s$  and  $G$  will be close to  $-C$ . Testing costs will be incurred just to confirm buyer's perceptions.

In what case, then, *would* a testing system be beneficial to growers? The net gains from testing are greatest when  $d_0$ , the stickiness discount, is large and  $S$ , the incidence of stickiness found by testing, is low. The discount  $d_0$  reflects buyers' *perceptions* of the incidence of stickiness in the region, while  $S$  is the *actual* incidence. So, testing will be most beneficial in a region where actual stickiness is much less prevalent than buyers believe. This might be the case in a region with a reputation for stickiness that has succeeded in combating it. Grading may also be beneficial for specific subregions within a larger region known for stickiness. For example, the current practice in Sudan is to mix lots from different origins. Freud and Bachelier (2001) argue that it would be better to identify and establish certified nonsticky production zones. Recognition of pest- and disease-free zones within countries has been adopted in international sanitary and phytosanitary agreements, allowing countries wider trading opportunities (Narrod and Malcolm 2002).

Gourlot and Frydrych (2001) developed a numerical application to estimate the potential benefits of establishing a stickiness grading system for Sudanese

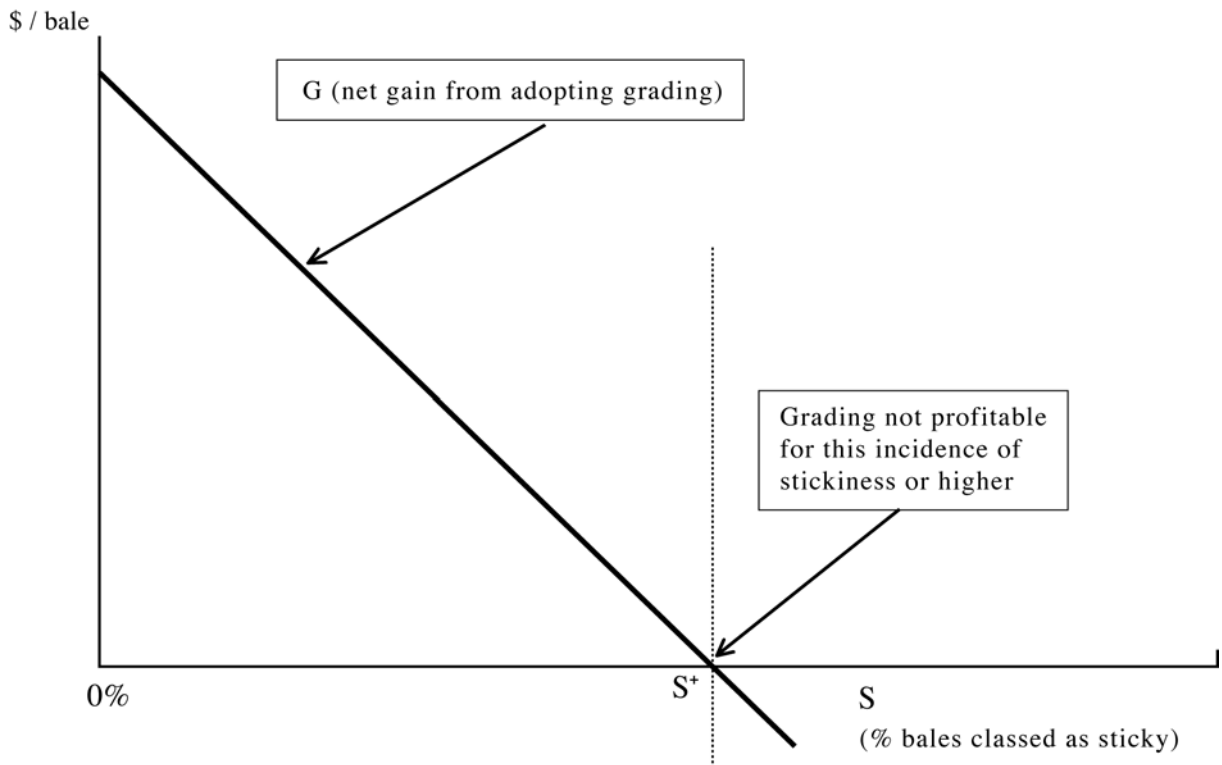


Figure 15. Relation of gains from adopting stickiness testing to incidence of stickiness.



cotton. They assumed a pregrading price discount of 7 percent, a grading cost per bale of \$1.51 (Watson 1998), and used prevailing prices for different types of Sudanese cotton. They constructed a schedule of net gains from grading that depended on the percentage of bales found nonsticky ( $1 - S$ ) and the discount imposed on bales found to be sticky,  $d_s$ . Their numerical results showed that if the discount imposed on bales found sticky were at least as large as the pregrading discount ( $d_s \geq d_0$ ), then between 60 and 80 percent of bales would have to be nonsticky for testing to be profitable for the country as a whole.

Ahmed and Latif (2001) conducted a similar numerical exercise for Sudanese cotton. They argued that Acala cotton in Sudan was most affected by stickiness, while most Barakat cotton was either free of stickiness or had only light stickiness. In their analysis, they assumed that cotton with up to 5 sticky points would be considered free of stickiness and receive a 10 percent price premium, while cotton with 6-15 sticky points would be considered lightly sticky and receive a 5 percent price premium. Cotton with 15 to 30 sticky points would be considered moderate and receive no premium or discount, while cotton above 30 sticky points would be classed as highly sticky and would

be penalized with a 5 percent discount. Given these pricing assumptions, they found gains from testing, particularly for Barakat cotton. Freud and Bachelier, however, have pointed out that Ahmed and Latif's estimated net gains from testing change to net losses if the discount on moderately sticky cotton was 5 percent and that on highly sticky cotton was 10 percent. They further question whether there would be any market for Sudanese cotton classed as highly sticky.

Given the demonstrable processing problems and economic losses that mills suffer because of sticky cotton and the historical examples of adverse market reactions to stickiness, it is questionable whether mills would be interested in purchasing cotton with any documented stickiness. Moreover, mills expect that any cotton they purchase should be free of stickiness. Therefore, payment of premiums for nonsticky cotton is unlikely.

### Summary and Conclusions

Several different sorts of contaminants may cause cotton lint to stick to moving surfaces during fiber processing, but by far the most common are insect honeydew sugars (Hector and Hodkinson 1989).

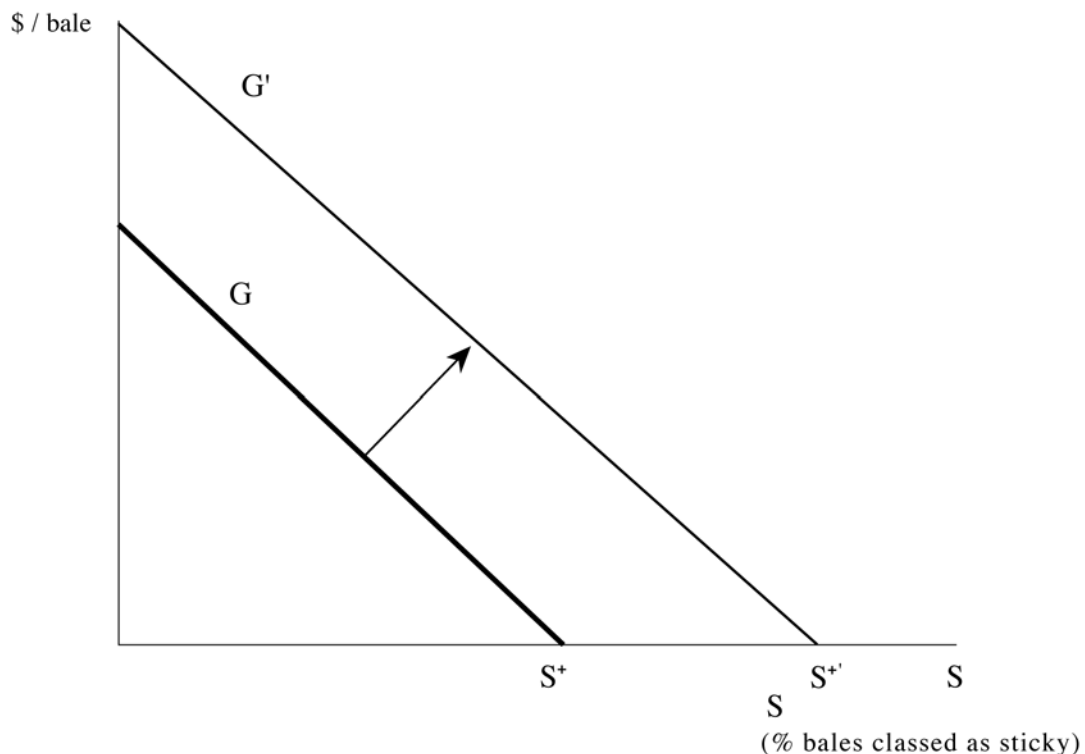


Figure 16. Result (increased net gains and scope) of adopting a stickiness testing system.

Studies that estimate the financial effect on textile mills are rare, but economic research done following an outbreak of sticky cotton in West Texas in 1995 suggests that losses were about 2-4 ¢/lb. Whereas initially the additional costs fall primarily on the mills that have unknowingly purchased sticky lint, in subsequent years purchasers tend to avoid or discount lint from the area that has produced sticky cotton. Lint from areas that have produced sticky cotton is discounted indiscriminately and the discount may persist well after the field problems have been corrected. The estimates of 3-5 ¢/lb (6-11 ¢/kg) discounts that have been suffered by Arizona growers following the stickiness episode of 1992 are comparable to the cost effects reported for mills that consumed 1995 crop West Texas cotton (Floek and Ethridge 1997, 1998, Ellsworth et al. 1999).

costs and longer term costs to growers in terms of reputation effects and stickiness prevention costs. However, it is not feasible with present technology to economically test bales for stickiness (chapter 13). Also, a testing system for sticky cotton would only be beneficial to growers under certain conditions, specifically in regions where actual stickiness is much less prevalent than buyers believe. This might be the case in a region with a reputation for stickiness that has succeeded in combating it. Given such limitations, the best defense against stickiness at the present appears to lie in better understanding of the basic causes, management in the field to minimize potential sources of stickiness, and effective education and exhortation by grower organizations to persuade their members to make earnest efforts to protect the reputation of their respective growing areas.

Imperfect information about cotton stickiness imposes near-term costs to mills in the form of extra processing

**Table 1. Level of contamination at which stickiness is likely to cause decreased efficiency**

<b>Processing point</b>	<b>Relative contamination level</b>
Carding machine, drawing frame	Light to very heavy
Ginning equipment	Moderate to very heavy
Harvesting equipment	Very heavy

**Table 2. Cotton aphid control costs for yield protection and stickiness prevention for selected states and the country, 1989-2001**

Year	Texas	California	Miss.	Arkansas	Louisiana	Tenn.	Other	U.S.
.....\$/harvested hectare .....								
1989	9.49	-	22.29	4.57	10.36	-	8.67	8.95
1990	3.71	4.76	17.01	14.50	7.51	-	5.31	6.31
1991	30.93	4.81	23.30	5.55	3.92	-	4.94	17.47
1992	6.13	2.73	13.23	3.53	5.40	-	5.71	5.96
1993	1.86	-	14.07	16.81	3.67	-	5.05	4.85
1994	5.42	75.15	5.06	4.84	2.50	-	1.01	9.65
1995	9.88	54.09	17.23	5.57	20.00	-	6.80	12.86
1996	4.88	11.92	5.84	3.74	3.07	0.00	0.98	3.85
1997	4.70	113.81	6.11	1.28	5.32	0.51	1.29	10.65
1998	4.12	9.17	6.05	2.47	18.36	1.67	2.53	4.49
1999	1.65	8.17	12.56	9.01	13.37	5.25	1.38	4.08
2000	8.93	15.72	8.30	4.16	8.53	3.06	2.69	6.60
2001	0.52	38.75	1.24	2.09	2.89	6.83	0.65	2.99
Average	7.09	30.82	11.71	6.01	8.07	2.89	3.62	7.59

Sources: Head 1990, 1991, 1992, 1993; Williams 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002.

**Table 3. Costs of sweetpotato whitefly control for yield protection and stickiness prevention in Arizona and California, 1992-2001**

Year	Arizona	California	Arizona	California	Both states
-----\$/hectare -----      ----- \$ million -----					
1992	116.40	2.60	37.6	2.6	40.2
1993	62.20	0.00	19.6	0.0	19.6
1994	88.10	0.00	27.5	0.0	27.5
1995	159.60	0.00	58.1	0.0	58.1
1996	59.60	3.00	18.7	3.0	21.7
1997	53.40	9.00	17.3	7.9	25.2
1998	35.90	1.80	8.9	1.1	9.9
1999	11.20	1.30	3.0	0.8	3.8
2000	19.40	2.30	5.4	1.8	7.2
2001	31.40	9.60	9.1	6.0	15.1
Avg. Total	63.70	3.00	205.2	23.0	228.3

Sources: Head 1993; Williams 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002.

**Table 4. Measures of sweetpotato whitefly damage and control costs in Arizona cotton**

	Average for--		
	1989-90 <sup>a</sup>	1992-95	1996-01
Hectares infested (%)	52	89	94
Hectares treated (%)	46	82	64
Insecticide applications per treated hectare	6.2	13.8	4.2
Whitefly control costs per treated hectare (\$/hectare) <sup>b</sup>	85.98	292.77	121.25
Whitefly-induced yield loss (%)	0.3	3.7	0.9
Whitefly share of total yield loss (%)	7.0	48.5	12.3
Statewide loss in cash receipts (\$ million) <sup>b</sup>	1.2	10.0	2.4
Statewide whitefly control costs (\$ million) <sup>b</sup>	7.5	38.2	10.0

Source: Head 1990, 1991, 1992, 1993; Williams 1994, 1996, 1997, 1998, 1999, 2000, 2001, 2002; and authors' calculations

<sup>a</sup> Data not available for 1991.

<sup>b</sup> 1996 constant dollars using GDP implicit price deflator.

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## Chapter 3

### Sources of Stickiness from Boll Development, Physiological Sugars, and Field Contaminants

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In the late 1970s and early 1980s, 80 to 90 percent of all cases of cotton stickiness were the result of insect contamination (Sisman and Schenek 1984), and during the last two decades the most common source of cotton lint stickiness has been contamination by insect honeydew (chapter 4). However, sugars from sources other than insects may contaminate cotton, and contaminants other than sugars may cause cotton to stick during processing. Sugars occur naturally in cotton as part of plant metabolism and fiber synthesis. Such sugars are known as physiological, or simply plant, sugars. The presence of physiological sugars above a critical content have been associated with sticking during fiber processing (Perkins 1971b).

Other contaminants that may cause sticking of lint during fiber processing include plant fragments, field trash, cotton or weed seed, and lubricants from harvesting or ginning equipment. Cotton is a natural product, and the composition of fiber may vary due to cultivar, crop maturity, and environmental conditions—especially in the weeks before harvesting—and exposure of open and harvested bolls to weather and microbial attack. Adverse environmental conditions at the end of the season, such as a succession of low night temperatures, may result in relatively immature fiber, particularly in bolls set at upper positions (Conner et al. 1972). Such bolls typically contain higher concentrations of low-molecular-weight sugars than do bolls with more mature fiber.

### Cotton Growth and Fruiting

Cotton is a perennial semishrub that is commercially grown as an annual in both tropical and warm temperate regions. Both upland and Pima cottons are indeterminate. Although cotton flowers in a regular progression, environmental conditions, including crop management, affect fruit retention; therefore, the relative vegetative-to-reproductive growth of cotton varies with field conditions, as does distribution of

bolls over the fruiting sites, and the sequence of boll development in the crop (Mauney 1986). In general, very favorable growing conditions produce rapid vegetative growth that adds sites for fruiting forms, but strong vegetative growth tends to suppress retention of fruiting forms and may delay crop maturity. In contrast, stress reduces the number of potential fruiting sites, but forces flowering of initiated fruit primordia, reinforces retention of the fruit that were set at the onset of stress, and accelerates maturity of the retained bolls.

Under good growing conditions, cotton plants begin producing floral buds, called squares, about 35-40 days after emergence, and continue to produce new squares on progressively higher main stem nodes until flowering ceases or “cuts out” (Oosterhuis 1990). Sympodial or fruiting branches arise alternately from the main stem. Squares first arise at the junctures of the main stem and the secondary branches. The next squares typically will be set at the juncture of the next higher node on the main stem about 3 days later, and at the next fruiting position further out on the same sympodial branch in about 6 days. Fruiting structures also may be produced on vegetative or monopodial branches. The rate of fruit development depends on accumulation of heat units, but flowers usually develop from squares in 15-21 days.

Cotton flowers are self-pollinating, but may also be pollinated by insects. Anthers produce fertile pollen and the stigma is receptive the first day of boll opening.

Flowers decline and petals close and dry within 3 days of first flowering. After anthesis, the cotton boll—the capsule containing seeds and the developing fibers emerging from the seeds—begins to mature and will open in about 50-55 days. With such continuous flowering, the cotton plant typically will have bolls of many ages and stages of maturity throughout the latter two-thirds of the growing season. As bolls are being set, the cotton plant continues to grow and produce leaf canopy.

Thus during the growing season, the cotton plant is continuously in a dynamic state of producing structure, adding leaves for photosynthetic capacity, and setting bolls that will compete with vegetative growth and with each other for the products of photosynthesis. In temperate climates, the latter half of the growing season is characterized by declining day length, declining diurnal accumulation of heat units, and—under favorable conditions—an increasing boll load



that itself will retard the continuing vegetative growth of the plant. Bolls are first set and first mature on the lower nodes; thus boll maturation proceeds up the plant from the bottom.

Harvest is typically timed to maximize potential yield while providing for timely gathering of the crop before fall rains can damage exposed open bolls or make the fields too wet for ready movement of harvesting equipment. Depending on the length of the growing season in the area, the maturity class of the cultivar, the level of fruit retention, and the growing conditions experienced during boll maturation, the harvestable bolls on a cotton plant may vary considerably in number and maturity at harvest. Clearly a large number of mature, open bolls is desirable. However, much cotton is mechanically picked or stripped when a range of maturities are represented by the bolls in a single field.

## Fiber Development

At anthesis, the cotton ovules are fertilized and seed development begins. Cotton fibers arise from epidermal primordia on the exterior of the seed coat. Mature cotton fibers are the walls of single highly elongated epidermal cells that grow from the surface of developing seeds (Kim and Triplett 2001). Each fiber develops in an ordered sequence of events. Fibers elongate for about 15-20 days. Thereafter the primary gain in fiber weight comes from secondary cell wall growth (Schubert et al. 1973). Rings of cellulose are deposited each day inside the previous day's growth. The fibers' walls thicken because of daily deposition of cellulose. Late in development, the fiber dries, collapses, and shrinks, resulting in fiber crimping and contortions.

By means of photosynthesis, all plants reduce carbon dioxide to monosaccharides, and use these sugars as sources of energy and as components to synthesize more complex organic molecules, polymers, and complex structures. The principal component of all plant secondary cell walls is cellulose, a molecule that is chemically a linear polymer of  $\beta$ -1,4 glucans. Cotton fibers are 95 percent or more cellulose but also contain soluble and insoluble carbohydrates, oligosaccharides, and small amounts of protein, pectin, and wax (Bertoniere et al. 1993). Natural cellulose polymers differ among sources as evidenced by differences in the relative amounts of extractable carbohydrates (Murray et al. 2001).

Both crystalline and noncrystalline cellulose are found in cotton, but in cotton fibers cellulose is typically small crystalline microfibrils arranged in multilayered structures (Lewin and Pearce 1998). The three-dimensional structure of cotton fibers has been imaged and described, but little is known about the three-dimensional assembly of cellulose in cotton fiber. It is probable that assembly of fibers requires several coordinated biochemical steps.

Chemical analysis of developing fibers shows that they contain glucose, fructose, sucrose, raffinose, stachyose, verbascose, melibiose, manninotriose, verbascotetrose, *m*-inositol, galactinol, and other sugars and sugar alcohols, some of which are as yet unidentified (Murray 1998). In addition there is a series of glucose-rich oligomers in cotton fiber whose relative concentrations vary with developmental and physiological parameters (Murray 1998, Murray et al. 2001, Murray and Nichols 2004). Absolute and relative concentrations of several soluble sugars and oligomers vary in a repeatable manner with time of day, days from anthesis, and relative position on the cotton main stem (Murray and Brown 1997, Murray and Munk 2000).

Accordingly, there are several different carbohydrates in each cotton boll, and the concentrations of the carbohydrates are changing continuously within the bolls as they develop and mature. Considered on a field basis, several cohorts of bolls are present at the same time. Each cohort represents the maturing fruits of flowers that attained anthesis on a particular day. Flowering that produces harvestable bolls extends over approximately a 4-week period for an early maturing cultivar in a short-season environment (110-120 day crop) and several weeks longer for a full-season variety in a long-season environment (130-150 day crop). Further, the rate of cotton fiber development varies among cultivars and is affected by date of planting, length of the growing season, accumulation of heat units, and cultural practices (Kittcock et al. 1981, Hague 2000).

Analyses of fiber collected from the field at regular intervals indicates that during the final few weeks of maturation, the total sugar content in fiber falls rapidly (Gameel 1969, Elsner et al. 1983). Gameel (1969) and Perkins (1971a) found that at 23 days before harvest, total sugars in the lint were as high as 15.9 percent, but fell to less than 0.3 percent at harvest. Cotton fibers that are less than fully mature at harvest may contain relatively high levels of the monosaccharides

glucose and fructose and the disaccharide sucrose (Hague 2000). Given the different flowering durations of cotton cultivars, it is clear that the susceptibility of cotton to stickiness from immature fibers may differ among different cultivars (Wyatt 1976, Perkins 1991, Hague 2000). Also, a number of environmental factors can contribute to a portion of the harvested cotton containing less than fully mature lint. Short growing seasons may be terminated by freezing weather, or there may be periods of low night temperatures or drought (Krieg and Sung 1986) or disease (Wyatt 1976, Perkins 1991), or the cotton may simply be harvested earlier than is optimum (Hector and Hodkinson 1989).

### **Fiber Weathering and Harvesting**

After bolls have opened, timely harvest generally is deemed necessary to preserve yields and quality. Precipitation and wind can cause fiber to be knocked to the ground. Rainfall typically washes soluble sugars from bolls, and therefore reduces the potential for stickiness; however, prolonged periods of high moisture content in the bolls can support microbial growth that may discolor the cotton (Hendrix et al. 2001). Microbial growth will consume some sugars, but may also synthesize and deposit other sugars. Clearly, the levels of sugars in the bolls, the amount and duration of rainfall and humidity, the exposure to various species and levels of inocula of microflora, and temperature during the period when open bolls are on the plant all interact to influence fiber weathering.

In one investigation, increased levels of sugars in cotton fibers were positively associated with microbial populations on the fiber (Domelsmith 1988). Thus, the level of microbial activity on cotton fiber was suggested as an indicator for the presence of sugars predisposing cotton lint to stickiness (Roberts et al. 1978, Domelsmith 1988). However, many microorganisms found on cotton fibers secrete enzymes that reduce fiber sugar content. Consequently, certain microbes and microbe-derived enzyme products have been suggested as means to reduce cotton stickiness (Elsner 1980, Blasubramanya et al. 1985, Heuer and Plaut 1985, Chun and Perkins 1996, Hendrix et al. 2001; also see chapter 10).

Freezing temperatures potentially have negative effects on cotton fiber and stickiness. In the High Plains of Texas, leaving cotton in the field to be terminated by freezing was considered a poor cultural practice because harvesting immature bolls that had been killed

by freezing increased the potential for sticky cotton in certain years (Hague et al. 1999). In some cases, cottons subjected to a freeze before maturity had been found to be very sticky (Shaw and Perkins 1991).

If lint is harvested before sugar concentrations decline to low levels, excessive amounts of physiological sugars may remain in cotton fibers and may cause stickiness problems during ginning and yarn manufacturing. There is evidence in such situations that timely harvesting can help to avoid sticky cotton (Hague et al. 1999). Timely use of ethephon, a boll opener, and paraquat, a crop desiccant, resulted in nonsticky cotton, while cotton from the same experiment that was terminated by a freeze showed a higher potential for stickiness (Hague et al. 1999).

### **Fiber Components Other Than Carbohydrates**

During the growth of cotton fibers, materials such as waxes and metal ions (probably salts of organic acids) are also found on the surfaces of maturing fibers, but these compounds do not appear to be related to cotton stickiness (Perkins 1971b). The presence and relative quantities of such components varies with time of season, cotton cultivar, and cultural practices. The relative content of such components also depends on weathering of fiber in the field and microbial activity on the fiber surface. Waxes and ionic molecules may, in fact, act as favorable aids in fiber processing. Fiber waxes seem to serve as a natural lubricant during yarn spinning. Removal of ionic molecules from lint before processing can lead to problems with static electricity. In addition to sugars, waxes, and ionic molecules, extracts of cotton fiber samples also commonly contain malic, fumaric, oleic, and linoleic acids (Roberts et al. 1978, Perkins et al. 1979, Cheung et al. 1980).

### **Sugars from Extrafloral Nectaries**

Cotton flowers have internal nectaries and leaf nectaries, and cotton cultivars that have not been bred intentionally to lack such organs have extrafloral nectaries at the base of the floral bracts. Sugars in the secretions of extrafloral nectaries consist entirely of sucrose and its components glucose and fructose (Mound 1962, Butler et al. 1972; also see chapter 4). Plant bugs (*Lygus* spp.) and other insects feed on extrafloral nectary secretions. Removal of the extrafloral nectaries was the target of a successful breeding effort, and the trait is called “nectarless” (Meyer and Meyer 1961).

Consideration was given to the possibility that sugars from extrafloral nectaries might fall on exposed lint and contribute to stickiness (Mound 1962, Hector and Hodkinson 1989). Observations by Evenson (1969) suggest that the nectar droplets run down the pedicels and under dry conditions form dry lumps near the base. Wyatt (1976) also observed that nectary secretions did not drop from leaf to leaf but remained hanging from the nectaries. Studies comparing cotton stickiness potential among nectaried and nectarless cultivars provided no evidence that external nectaries are a significant source of contamination (Hague 2000.) Since virtually all commercial cotton cultivars have nectaries and the presence or absence of nectaries is not correlated with stickiness, we find no evidence that nectaries are a significant source of contamination leading to lint stickiness.

### **Field Contaminants**

Cotton leaf fragments contain the same physiological sugars as extracts of clean cotton lint. In addition, a number of less abundant sugars may be found. High trash levels as well as oily seed coat fragments may be generated at the gin and not removed by lint cleaning. Such trash may cause oily or sticky deposits on crush rolls and other processing equipment. When the thin fiber web passes through the crush rolls, fibers may stick to the rolls at points where seed particles have been crushed or oil released. Fine leaf trash containing high levels of plant sugars may also cause processing stickiness problems under certain conditions (Wyatt 1976).

Ginning and lint processing aids such as lubricants and antistatic agents, if improperly applied, have been reported to cause stickiness (Perkins 1971b). Also, accidental contamination of cotton with oil and grease from picker-head mechanisms during harvesting or from grease at gin presses occasionally have resulted in fiber stickiness (Perkins 1975, Perkins and Bragg 1977). A number of techniques have been used by textile mills to deal with field contaminants; these are reviewed in chapter 13.

### **Sugar Content and Fiber Processing**

Presence of physiological sugars in sufficient quantities can sometimes cause lint stickiness (Mound 1962, Gutknecht 1988, Perkins 1983). In recently open bolls and other cotton that shows no sign of

microbial activity, the most abundant sugars are the monosaccharides glucose and fructose, followed by the disaccharide sucrose (Elsner 1982, Hague 2000). However, several additional carbohydrates may be found in cotton fiber. Brushwood and Perkins (1996) identified nine different plant sugars and sugar alcohols (polyols) in cotton fiber that was known to be free from honeydew contamination.

In efforts to screen for potential lint stickiness, textile processors use simple reducing sugars tests (Carter 1990, 1992; also see chapter 13). An absolute level of reducing sugars associated with stickiness during processing has not been defined, but a reducing sugar content in the range of 0.3-0.4 percent, as determined by titration with potassium ferricyanide, may be used as a discriminating level to screen bales for potential stickiness (Perkins 1971a). However, different sugars cause different levels of lint stickiness (Miller et. al. 1994). For example, sucrose is significantly stickier than either glucose or fructose. Because of the specificity of the effects of the different sugars, it is important to know the identity of the sugars that are detected in order to develop an effective strategy to avoid stickiness during fiber processing (see chapter 14).

Processing cotton fibers that have excessive levels of plant sugars can result in a gradual buildup of sticky deposits on processing machinery. The problem usually begins with accumulation of sugar residues at the picker calendar rolls. Sugars may then be carried forward, and additional problems may occur at carding, roving, and spinning. Severe sticking at the carding stage can cause fiber to adhere to the crush rolls, interrupting web formation. Stickiness causes lapping in roving and ends down in spinning due to the accumulation of sugars and other materials on the rolls. Frequent shutdowns to clean sugars from machinery may be necessary when stickiness becomes chronic (Lalor 1992). While textile mill equipment is being cleaned, production efficiency declines and mills lose income from lost production. Strategies that may be used by textile mills to process sticky cotton or to manage inventories of cotton that have evidenced sticking during process are discussed in detail in chapter 14.

## Summary and Recommendations

Avoiding stickiness due to excessive levels of physiological sugars in harvested bolls is best achieved by managing the crop for timely cutout, or termination of flowering, followed by appropriate use of harvest aids and timely harvesting before the onset of adverse weather.

Managing for timely cutout may be achieved by matching the maturity class of the cultivar with the available heat units in the planting area, planting as early as practical, matching fertilizer (especially nitrogen fertilizer) to realistic yield goals, and managing for 60 percent or greater square retention by timely and effective treatment of insects and use of plant growth regulators. If the cotton crop cuts out before low night temperatures begin, the crop typically is easily defoliated or desiccated, and picking or stripping can proceed 10-12 days after the harvest aids have been applied, providing the weather is dry.

Effective in-season weed management is needed for good yields and greatly facilitates harvesting and ginning. If there are weed escapes, remedial end-of-season weed desiccation may be helpful.

At the gin, lint moisture content should be controlled and gin stand settings should be adjusted to effectively remove plant and weed trash from the seed cotton. Contamination of fiber with all foreign materials should be avoided. Pickers, strippers, and ginning equipment should be kept in good repair, and equipment and shops should be clean and kept orderly to avoid accidental contamination with lubricants (Perkins 1983, Lalor 1992).

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## Chapter 4

### Sweetpotato Whitefly, Bandedwinged Whitefly, and Cotton Aphid Honeydew Carbohydrates

*D.L. Hendrix and D.E. Brushwood*

Sweetpotato whiteflies, bandedwinged whiteflies (*Trialeurodes abutiloneus* (Hadelman)), and cotton aphids ingest large quantities of plant phloem sap, which characteristically contains very high concentrations of sucrose (Tarczynski et al. 1992). Phloem sap can have an osmotic concentration of up to three times that of the insects' hemolymph, which could potentially cause them fatal osmotic problems (Downing 1978, Ashford et al. 2000). Phloem-feeding insects convert most of the sucrose they ingest into one or more oligosaccharides in their gut, reducing the water gradient between their gut lumen and hemolymph. These oligosaccharides are then excreted as droplets of a concentrated syrup known as honeydew.

Worldwide, sweetpotato whitefly and cotton aphid honeydew are the cause of 80 to 90 percent of the stickiness observed in cotton lint (Rimon 1982, 1984, Watson et al. 1982, Sisman and Schenek 1984, Hector and Hodkinson 1989, Hague 2000). In rare cases, cotton fiber can become contaminated with honeydew from bandedwinged whiteflies (Clower and Watve 1973, Hendrix et al. 2002). For completeness, a brief description of its honeydew chemistry is included.

#### Sweetpotato Whitefly Honeydew

Henneberry et al. (1999) reported that each adult sweetpotato whitefly, feeding on cotton leaves in the laboratory, excreted between 25 and 64 drops of honeydew each day; and even higher rates of honeydew excretion have been observed for adult whiteflies on field-grown cotton and immature whiteflies in the laboratory (Gameel 1969, Costa et al. 1999). Salvucci et al. (1997) measured the rate of excretion of adult whiteflies on artificial feeders and determined that each whitefly produced 6 nL of honeydew per hour. Heavily

infested cotton leaves can contain up to 300 adult and 4,000 immature sweetpotato whiteflies (Naranjo and Hutchison 1997, Lin et al. 2000b). If this many adult whiteflies excreted honeydew at the rate measured by Salvucci et al. (1997), daily honeydew output would equal 43  $\mu$ L per leaf. However, the rate of honeydew output by these adults would be eclipsed by the 500  $\mu$ L of honeydew excreted each day by the immatures on these leaves (assuming that the honeydew droplets of the immatures and adults are of similar size and that their honeydew output was constant during the day and was not diminished significantly by such a high concentration of insects).

If we assume that the sugars in this excreta are equivalent to 350 mM sucrose, such an infestation would cause a loss of approximately 60 mg of sucrose per leaf per day, which is faster than the average uninfested cotton leaf synthesizes sucrose under field conditions (Wullschleger and Oosterhuis 1990). This sucrose loss problem is made more acute by the fact that cotton leaves infested by sweetpotato whiteflies synthesize and export sucrose at significantly reduced rates (Yee et al. 1996, Lin et al. 2000a,b). If the sucrose demands of infestations of immature whiteflies of this magnitude continue very long they can result in defoliation and death of all plants in a cotton field (Gameel 1969, 1978). Even though whiteflies excrete large quantities of sugar each day, the amount they eliminate as honeydew is only 50 to 70 percent of the sugars they ingest, the remainder being metabolized to maintain their unusually high metabolic rate (Salvucci et al. 1997, Salvucci and Crafts-Brandner 2000).

Both the insect species and the species of plant on which the insects feed influences the type and relative abundance of sugars in honeydew (Hendrix et al. 1992, Isaacs et al. 1998). Each species of plant translocates a specific set of sugars (and sometimes sugar alcohols as well) in their phloem that can potentially appear in honeydew (Zimmermann and Ziegler 1975).

One common feature of the most abundant phloem-translocated sugars and sugar alcohols is that they are all nonreducing. Not only are the sugars in the diet of insects that feed on plant phloem nonreducing, but nearly all of the oligosaccharides in their honeydew are nonreducing as well (Bates et al. 1990, Hendrix and Wei 1994, Wei et al. 1996, 1997, Hendrix 1999).

High performance liquid chromatography (HPLC) analysis of the products of the acid digestion of

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sweetpotato whitefly and cotton aphid honeydew revealed that the oligosaccharides in excretions of each insect consist of approximately 90 percent glucose and 10 percent fructose monomers (Hendrix 1999). This is somewhat surprising because these sugars are all synthesized from sucrose, which is 50 percent glucose and 50 percent fructose (Salvucci et al. 1997). The fate of much of the fructose that results from sucrose hydrolysis is unknown. Some is excreted (table 1) and an additional portion could be converted to glucose; but, given the very large rate of sucrose hydrolysis by these insects and the energy requirement for this conversion (Hendrix 1999), it seems unlikely that much of the fructose released in sucrose hydrolysis is rerouted into glucose. During the hottest part of the day or under water stress conditions, a substantial amount of the fructose derived from sucrose hydrolysis by sweetpotato whiteflies is converted into sorbitol, which accumulates in their blood (hemolymph) (Salvucci et al. 1998, Wolfe et al. 1998).

The major sugar in sweetpotato whitefly honeydew is the unusual disaccharide trehalulose ( $\alpha$ -D-glucose-(161)-D-fructose), which constitutes approximately 40 percent of the total oligosaccharides in this excreta (table 1). Although the anomeric carbon of the fructose moiety in trehalulose (carbon number 2) is not substituted, this sugar is weakly reducing. Trehalulose is therefore not easily quantified using copper ion reducing sugar tests (Hendrix and Wei 1992). Nearly all of the other oligosaccharides in sweetpotato whitefly honeydew are also nonreducing (Benedict's and Fehling's tests), but these sugars can all be quantified using the potassium ferricyanide test (Perkins 1971a,b, 1993, Brushwood and Perkins 1993).

Early attempts to identify the sugars in sweetpotato whitefly honeydew using chromatographic methods failed to detect trehalulose, the most abundant sugar (Roberts et al. 1976, Bourely 1980, Cheung et al. 1980, Bourely et al. 1984, Sisman and Schenek 1984, Gray et al. 1985). This was likely due to the difficulty in distinguishing trehalulose from sucrose using older chromatographic techniques and to the lack of trehalulose standards. Finally, however, Bates et al. (1990) isolated this unusual disaccharide from sweetpotato whitefly honeydew using HPLC and determined its structure by means of nuclear magnetic resonance spectroscopy. Hendrix et al. (1992) confirmed the existence of trehalulose as the predominant sugar in this honeydew using gel filtration chromatography and isocratic normal phase HPLC.

They also confirmed the existence of the trisaccharide melezitose ( $\alpha$ -D-glucose-(1 $\rightarrow$ 3)- $\beta$ -D-fructose-(2 $\leftrightarrow$ 1)- $\alpha$ -D-glucose) and its degradation product turanose ( $\alpha$ -D-glucose-(1 $\rightarrow$ 3)-D-fructose) in this honeydew; these sugars had been previously found by several researchers (Perkins 1983, Milnera et al. 1984, Gray et al. 1985, Moore et al. 1987).

Using gradient elution anion exchange HPLC, Hendrix and Wei (1994) demonstrated that there are at least two dozen sugars in sweetpotato whitefly honeydew (figure 1). The method they employed for this analysis does not detect turanose because it coelutes with other sugars, but it does resolve many other sugars not detected by methods used previously. The detector used in this method, pulsed amperometric detection, is very sensitive, but it responds differently to various sugars (Larew and Johnson 1988). Thus, while this method can detect very small quantities of sugars and can resolve complex oligosaccharide mixtures, peak sizes in the resulting chromatograms are not directly related to the amount of sugars injected. In order to get an accurate picture of the relative amounts of sugars in this honeydew, Wei et al. (1996) used an evaporative light-scattering HPLC detector and gradient elution normal phase chromatography (compare figure 2 to the upper panel in figure 1). Their results using the light-scattering detector showed trehalulose to be the predominant sugar in this honeydew and that 37 percent of the sugars in this oligosaccharide mixture were the size of trisaccharides or larger (calculated from table 1 by adding percentages of bemisiose, bemisiotriose, melezitose, and "all other sugars"). Wei et al. (1996, 1997) also found a number of sugars in honeydew that have very unusual structures, such as bemisiose ( $\alpha$ -D-glucose-(1 $\rightarrow$ 4)- $\alpha$ -D-glucose-(1 $\leftrightarrow$ 1)- $\alpha$ -D-glucose), a trisaccharide that had not been previously reported in higher organisms, and diglucomelzitolose ( $\alpha$ -D-glucose-(1 $\rightarrow$ 4)- $\alpha$ -D-glucose-(1 $\rightarrow$ 3)- $\beta$ -D-fructose-(2 $\leftrightarrow$ 1)- $\alpha$ -D-glucose-(4 $\leftarrow$ 1)- $\alpha$ -D-glucose), a pentasaccharide that had not been previously reported in the chemical literature.

To determine the relative stickiness of the sugars in sweetpotato whitefly honeydew, Wei et al. (1997) removed honeydew by washing a bale of honeydew-contaminated cotton and separated its sugars using a column consisting of equal parts of charcoal and diatomaceous earth (Whistler and Durso 1950). Sugars of various sizes were obtained from this column by eluting with increasing concentrations of isopropanol in water. The largest honeydew sugars were obtained



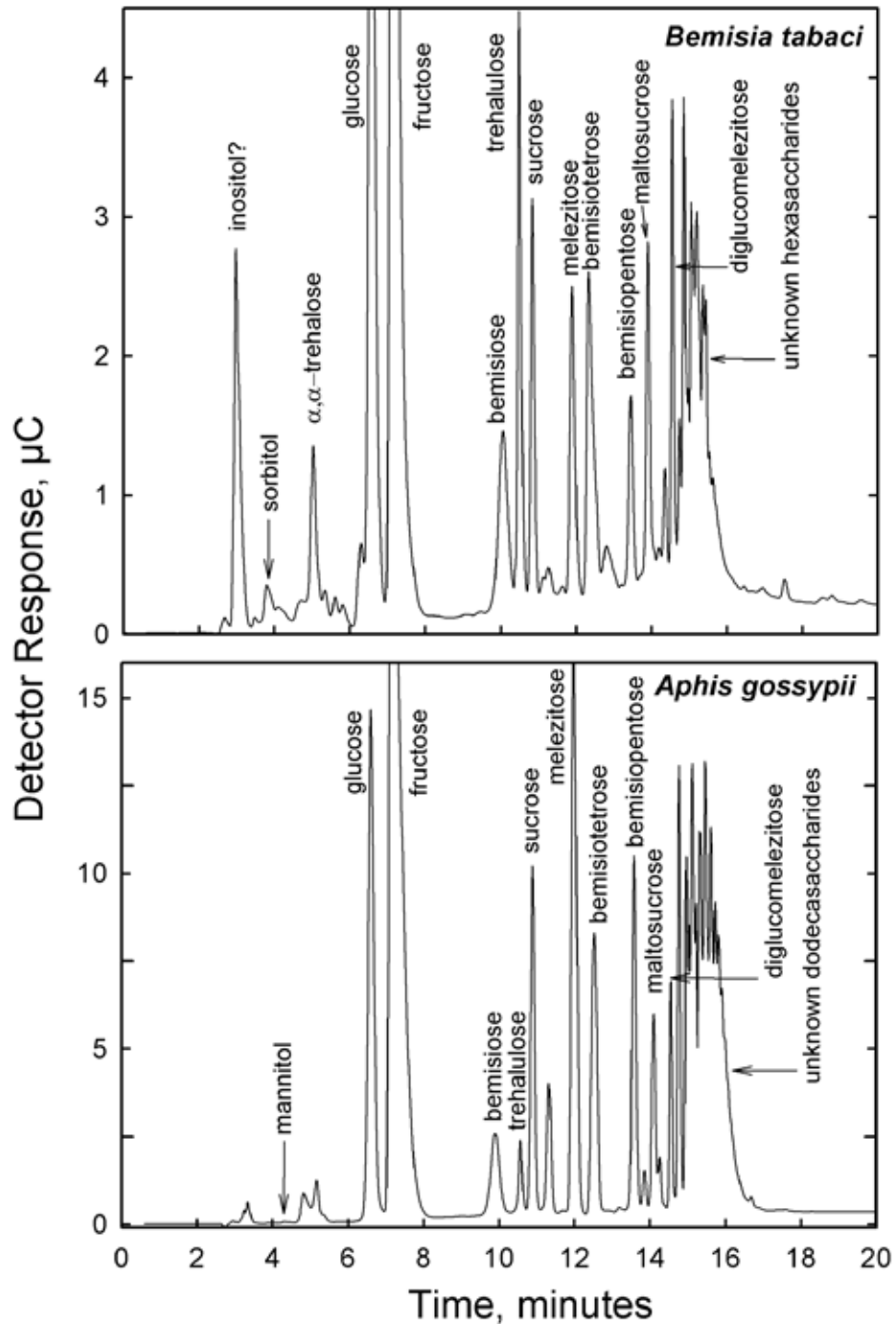


Figure 1. Anion HPLC analysis of the honeydew secreted by the sweetpotato whitefly (*B. tabaci*) and cotton aphid (*A. gossypii*). Method of analysis detailed in Hendrix and Wei (1994). Note that the response of this detector differs for different sugars (Larew and Johnson 1988).

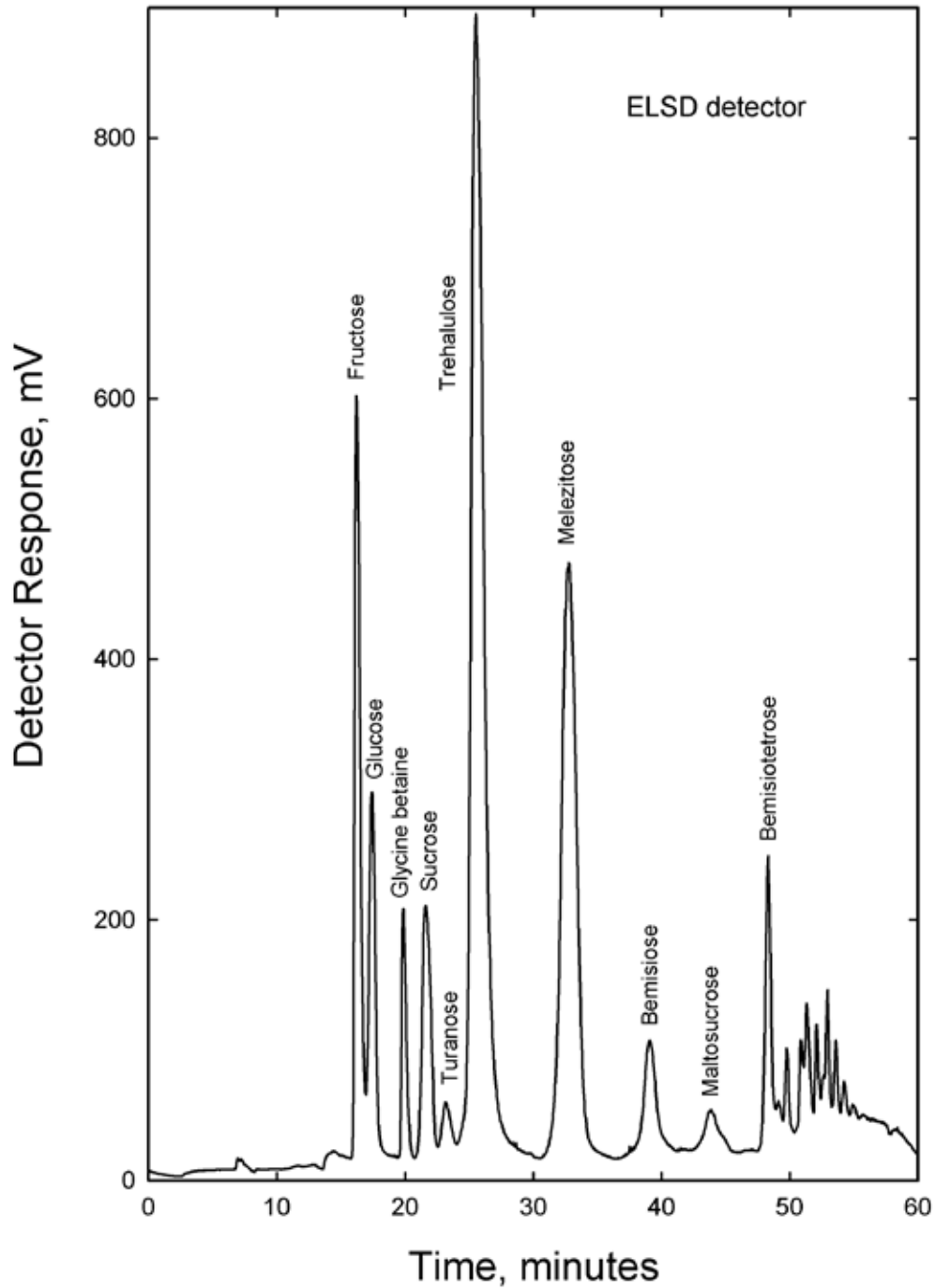


Figure 2. HPLC analysis of the honeydew secreted by the sweetpotato whitefly using a  $\text{NH}_2$  column and evaporative light-scattering detector (Wei et al. 1996). The response of this detector is proportional to the mass of nonvolatile material eluted from the HPLC column.

by eluting this column with 4 and 6 percent isopropanol (Hendrix 1999; see also figure 3). These large sugars were found to be significantly sticky when sprayed on clean cotton (Henneberry et al. 2000a), demonstrating that even the largest sugars in this honeydew contribute to the sticky nature of this honeydew.

At maturity, cotton seeds contain high amounts of the galactose-containing oligosaccharides raffinose ( $\alpha$ -D-galactose-(1 $\rightarrow$ 6)- $\alpha$ -D-glucose-(1 $\leftrightarrow$ 2)- $\beta$ -D-fructose) and stachyose ( $\alpha$ -D-galactose-(1 $\rightarrow$ 6)- $\alpha$ -D-galactose-(1 $\rightarrow$ 6)- $\alpha$ -D-glucose-(1 $\leftrightarrow$ 2)- $\beta$ -D-fructose) (Doman et al. 1982, Hendrix 1990). Therefore, these two oligosaccharides and their degradation products, melebiose and mannanotriose (Davis et al. 1993), would be expected to appear in extracts of cotton fiber contaminated with seed fragments. These nonreducing galactosides are translocated in the phloem sap of certain plants, and therefore they and their degradation products are found in whitefly honeydew when whiteflies feed on plants such as melons and ash trees (Byrne and Miller 1990, Davis et al. 1993). However, since these galactosides are not found in cotton phloem sap (Tarczynski et al. 1992), they are not found in the honeydew of insects that feed on cotton phloem. They are also not found in developing cotton fibers or extrafloral nectaries (figure 4).

The synthesis and excretion of oligosaccharides by whiteflies and other phloem-feeding homopterans is thought to play a crucial role in their osmotic regulation (Fisher et al. 1984, Salvucci et al. 1997, Wilkinson et al. 1997). For example, Downing (1978) showed that the hemolymph osmotic pressure of the body fluids of green peach aphid (*Myzus persicae*) remained relatively constant when the osmolarity of their phloem sap diet increased three-fold. He noted that this aphid carried out osmotic adjustments of its gut contents and thereby avoided large osmotic gradients between its gut lumen and hemolymph. Fisher et al. (1984) and Rhodes et al. (1997) showed that aphids achieve this osmotic adjustment by increasing the average size of the oligosaccharides in their intestinal contents, which is reflected in an increased average size of the oligosaccharides in their honeydew. Increasing the sucrose content of the sweetpotato whitefly's diet also increases the abundance of larger oligosaccharides in its honeydew (figure 5), suggesting that whiteflies also share this mechanism of osmoregulation.

The nonreducing disaccharide trehalose ( $\alpha$ -D-glucose-(1 $\leftrightarrow$ 1)- $\alpha$ -D-glucose), commonly found in insect

hemolymph, is present in unusually high levels in the bodies of sweetpotato whiteflies (Hendrix and Salvucci 1998) compared to its content in other insects (Mullins 1985, Bedford 1997). It also is present in significant concentrations in sweetpotato whitefly honeydew (figure 1). Several of the sugars in this honeydew also contain the trehalose moiety (Hendrix and Wei 1994, Wei et al. 1996), suggesting that they are synthesized from trehalose.

Not all sugars found in high concentrations in the bodies of sweetpotato whiteflies appear in their honeydew. Sweetpotato whiteflies accumulate high concentrations of isobemisiiose ( $\alpha$ -D-glucose-(1 $\rightarrow$ 6)- $\alpha$ -D-glucose-(1 $\leftrightarrow$ 2)- $\beta$ -D-glucose) and the sugar-like alcohol (polyol) sorbitol within their bodies to achieve tolerance of both high temperature and dietary osmotic stress (Salvucci et al. 1998, Hendrix and Salvucci 1998, Wolfe et al. 1998, Hendrix and Henneberry 2000, Hendrix and Salvucci 2000). Neither of these compounds appear in more than trace levels in sweetpotato whitefly honeydew (figure 1), although trace amounts of sorbitol appear in cotton leaves but not in phloem sap (figure 4). Sweetpotato whiteflies convert diet-derived fructose into high concentrations of sorbitol during osmotically stressful periods. In the field, the sorbitol concentration of their body fluids rises rapidly to about 400 mM during morning hours and rapidly returns to very low levels in the evening (Hendrix and Henneberry 2000). A variety of osmotic stresses, including feeding on water-stressed plants and diets with high sucrose content, can trigger sorbitol synthesis in these insects (Hendrix and Salvucci 1998, Wolfe et al. 1998, Hendrix 1999). Upon removal of the osmotic stress, the sorbitol that accumulated in the hemolymph of these insects disappears rapidly. It is apparently converted back to fructose rather than being excreted.

Various factors can influence the composition of honeydew. The developmental stage of the sweetpotato whitefly can change the relative abundance of sugars in its honeydew, but the sugars in the honeydew of older nymphs are fairly similar to that of adult insects (Costa et al. 1999). The sex of the insect has a pronounced effect on the sugar composition of honeydew. The honeydew secreted by adult male sweetpotato whiteflies contains far fewer sugars, an abundance of sucrose, and almost no trehalulose compared to that from adult females (Hendrix 1999). As mentioned previously, the concentration of sucrose in the insect's diet also changes the relative abundance of sugars in

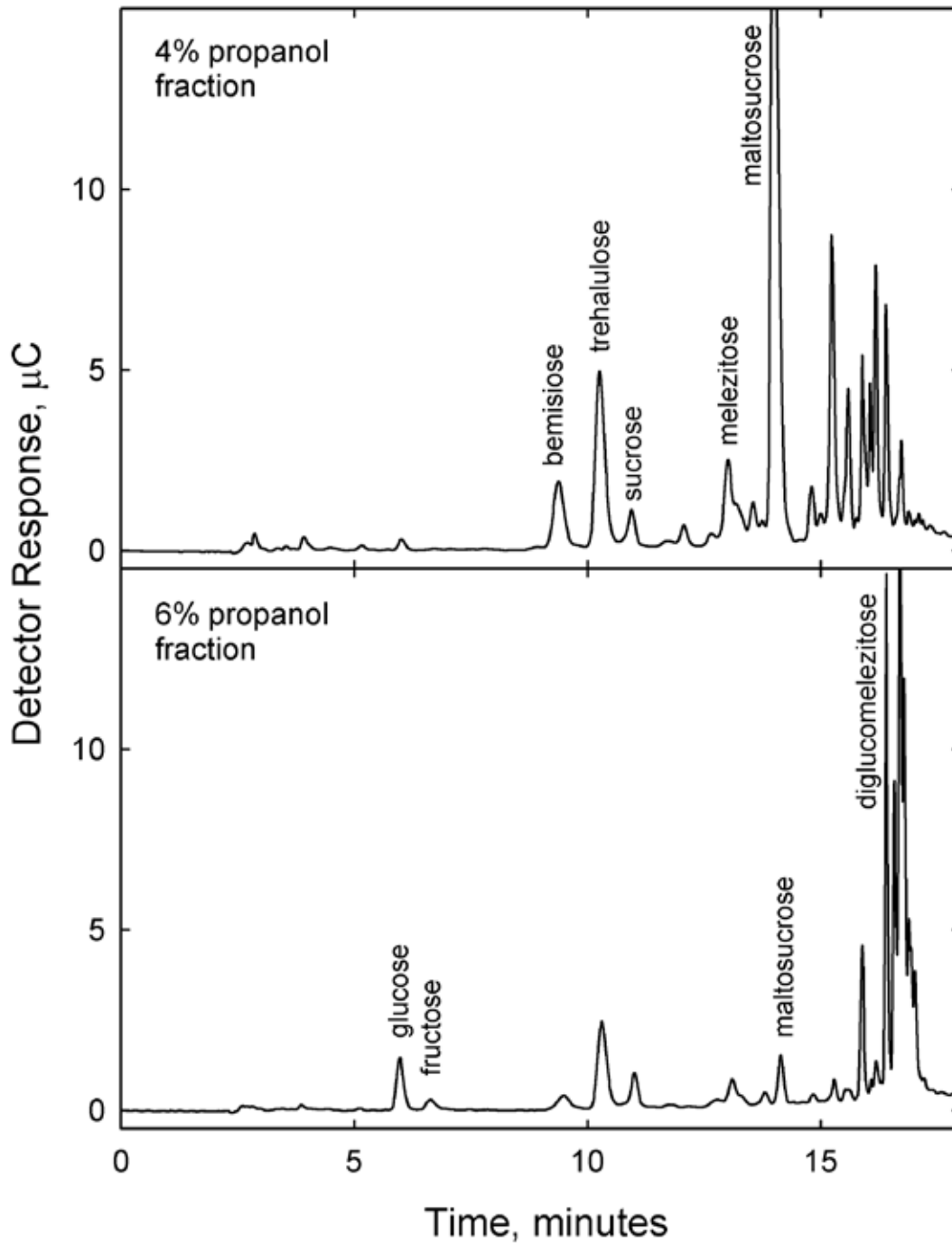


Figure 3. HPLC analysis of sweetpotato whitefly honeydew fractionated on a charcoal:diatomaceous earth column. Sugar fractions were eluted from this column with increasing concentrations of isopropanol. Sugars eluted with 4% and 6% propanol are shown.

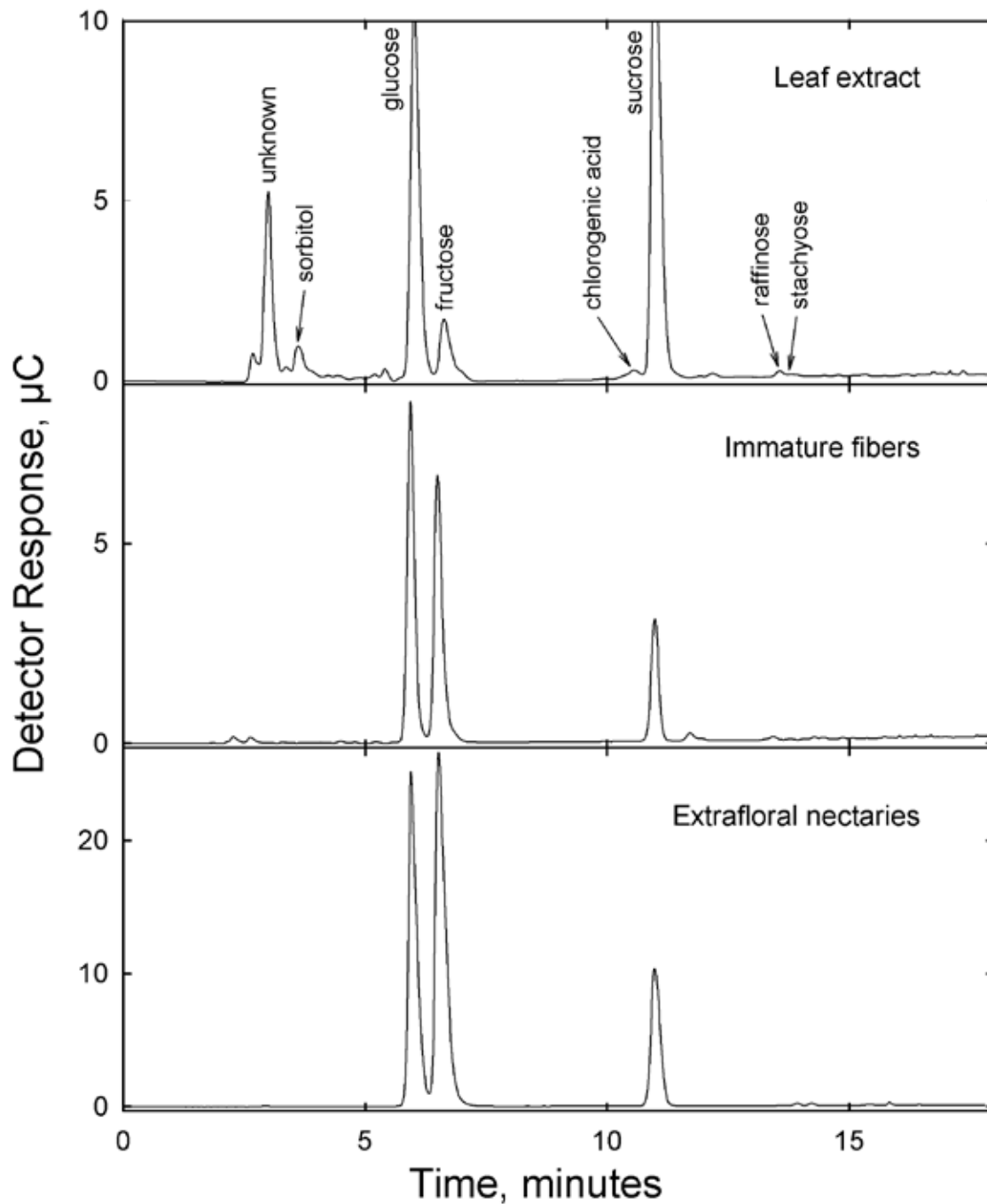


Figure 4. Anion HPLC analysis of the sugars in a mature cotton leaf, immature fibers from a boll which has just started to open, and the extrafloral nectar secreted by upland cotton (*Gossypium hirsutum* L.) leaves.

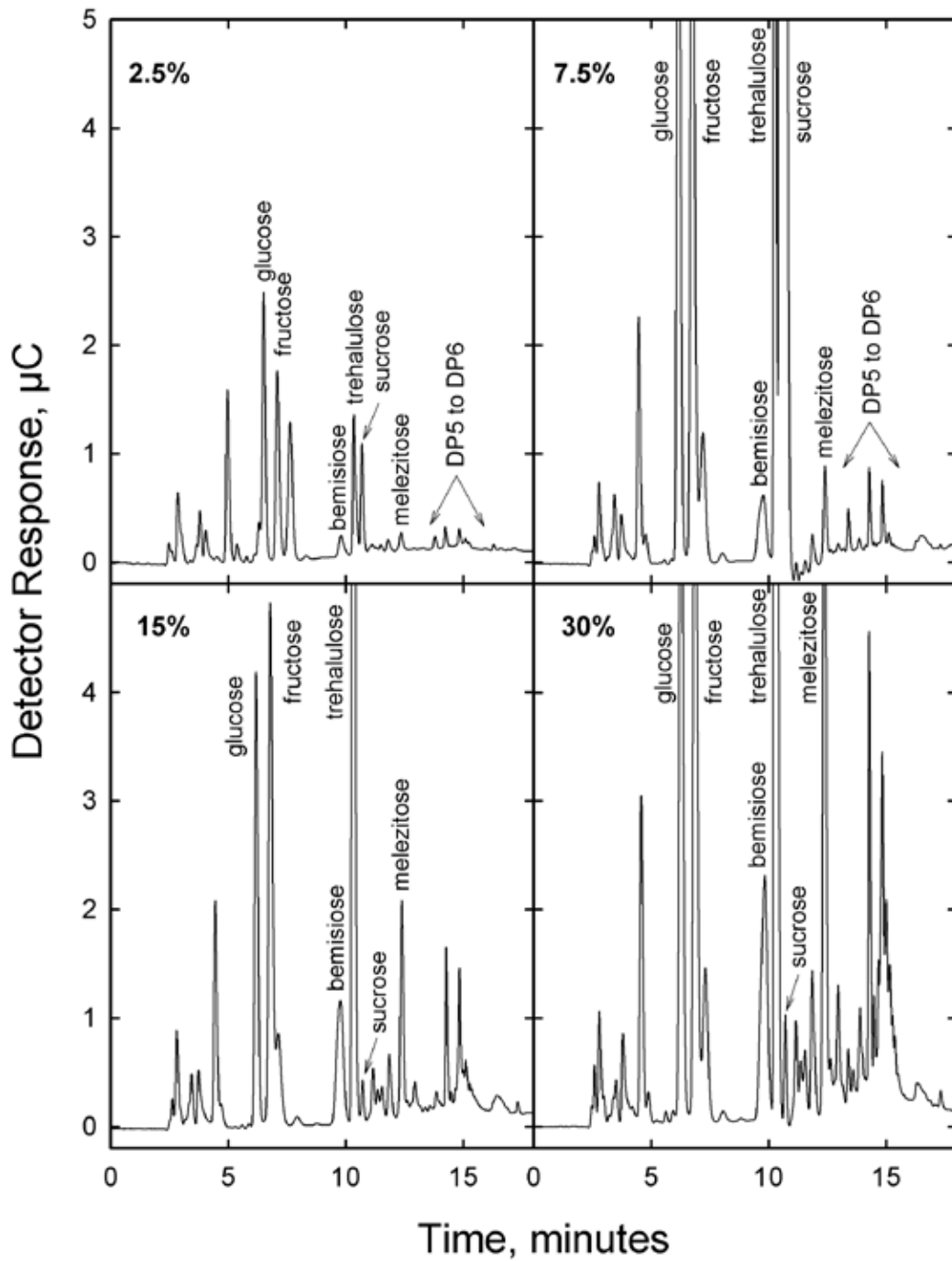


Figure 5. Anion HPLC chromatographs of honeydew secreted by *B. tabaci* feeding upon artificial diets containing 2.5, 7.5, 15 and 30% sucrose (M.E. Salvucci and D.L. Hendrix, unpublished data).

its honeydew as well as influencing its internal sorbitol content.

### **Bandedwinged Whitefly Honeydew**

Bandedwinged whitefly honeydew is more difficult to identify and distinguish from plant sugars as it does not contain any of the three oligosaccharides that characterize sweetpotato whitefly or cotton aphid honeydew. In addition, bandedwinged whitefly honeydew characteristically contains only small amounts of the large oligosaccharides that are characteristic of honeydew from the other two insects. The major sugar component of bandedwinged whitefly honeydew appears to be glucose (Hendrix et al. 2002).

### **Cotton Aphid Honeydew**

Honeydew secreted by cotton aphids typically contains only a small amount of trehalulose, but often (though not always) it contains large concentrations of the trisaccharide melezitose (figure 1; see also Hendrix et al. 1992). As with sweetpotato whitefly honeydew, honeydew from cotton aphids feeding on the cotton plant contains mainly nonreducing sugars. However, the largest saccharides in cotton aphid honeydew are considerably larger than the largest sugars in sweetpotato whitefly honeydew. Estimates from the results of anion HPLC analyses of cotton aphid honeydew sugars separated by gel filtration suggest that the largest sugars in this honeydew are at least as large as decasaccharides, which is nearly twice as large as the largest sugars in sweetpotato whitefly honeydew (Hendrix 1999). Both sweetpotato whitefly and cotton aphid honeydews have been found to consist mostly of reducing sugars, and the monosaccharides that make up the oligosaccharides in both of these excretions are approximately 90 percent glucose and 10 percent fructose (Hendrix 1999). Small aphids lack both malpighian tubules and filter chambers (Ponsen 1979). It seems possible that cotton aphids produce larger honeydew saccharides because they depend more on this mechanism of osmoregulation (Fisher et al. 1984, Rhodes et al. 1997, Ashford et al. 2000) than whiteflies, which have both of these structures (Weber 1995).

Maxwell and Painter (1959) found that a number of factors influenced honeydew production by aphids, including the environmental temperature. Aphid honeydew production increased with increasing air temperature. These researchers found that the location

on the plant, plant illumination, and plant variety all influenced the rate of aphid honeydew output. Zang et al. (1985) found that immature cotton aphids feeding on cotton excreted 71 percent of the phloem sap sugars they ingested, which is comparable to that observed for adult sweetpotato whiteflies (Salvucci et al. 1997, Salvucci and Crafts-Brandner 2000). For both aphids and whiteflies, honeydew excretion is a process that continues both day and night, although the rate of honeydew excretion varies significantly diurnally (Gameel 1969, Costa et al. 1999, Hendrix and Henneberry 2000). The rate of honeydew droplet production by individual cotton aphids is slower than the droplet formation rate for whiteflies, but cotton aphids, being three times larger than sweetpotato whiteflies, produce significantly larger honeydew droplets (Henneberry et al. 2000b).

When exposed to high temperatures, cotton aphids accumulate high concentrations of the sugar alcohol mannitol (Hendrix and Salvucci 1998). This polyol, like the sorbitol accumulated by osmotically stressed whiteflies, is created from diet-derived fructose. Mannitol formation from fructose in cotton aphids, like sorbitol formation in whiteflies, is carried out by an unusual NADPH-requiring ketose reductase enzyme. Mannitol accumulates at much higher concentrations in aphids' bodies than sorbitol does in sweetpotato whiteflies, but like sorbitol in whiteflies, mannitol does not appear at more than trace levels in aphid honeydew (figure 1).

### **Individual Sugars and Cotton Lint Stickiness**

The sugars found in cotton insect honeydew are not equally sticky. Miller et al. (1994), using a minicard stickiness detector (described in chapter 5), found that two of the sugars prominent in these honeydews, sucrose and trehalulose, were very sticky when applied to clean cotton lint. Melezitose and the monosaccharides glucose and fructose were found to be significantly less sticky than sucrose and trehalulose. In several years of field experiments, Henneberry et al. (1995, 1996, 1998, 2000a) found that the amounts of trehalulose and melezitose on lint contaminated by sweetpotato honeydew correlated significantly with lint stickiness. They found that the presence of other honeydew sugars were less correlated with lint stickiness as determined by the sticky cotton thermodetector method (described in chapter 5) (Brushwood and Perkins 1993).

**Table 1. Relative abundance of sugars and glycine betaine in *Bemisia tabaci* honeydew detected by HPLC and evaporative light-scattering detector**

Sugar	Percentage of total solids
Bemisiose	2.8
Bemisiotetrose	4.7
Fructose	10.5
Glucose	5.6
Glycine betaine	2.7
Melezitose	21.7
Sucrose	5.4
Turanose	1.3
Trehalulose	36.6
All other peaks*	8.7

Source: Wei et al. 1996

\* Trisaccharides or larger.

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## Chapter 5

### Sweetpotato Whitefly and Cotton Aphid Honeydew Production and Relationship to Cotton Lint Stickiness

*T.J. Henneberry and D.L. Hendrix*

Recognition of the role of insect honeydew as an important factor in cotton stickiness problems stimulated much research to define this relationship and develop methods to identify and quantify honeydew sugars on sticky cotton before they enter textile mill processing systems. The application of gradient anion high performance liquid chromatography (HPLC) as a technique to quantify the saccharides extracted from lint (Hendrix and Wei 1994, Wei et al. 1996, 1997; also see table 1) has resulted in major contributions to our knowledge of the carbohydrate composition of insect honeydews and clarification of their role in cotton lint stickiness.

Cotton lint stickiness as discussed in this chapter was determined with the sticky cotton thermodetector (SCT) (Brushwood and Perkins 1993) described in chapter 13. In this chapter, we report research on (a) honeydew production by sweetpotato whiteflies and cotton aphids and (b) lint stickiness laboratory studies with sprays of rehydrated honeydew extracted and lyophilized from cotton lint, with isopropyl alcohol extracts of the large saccharides from honeydew (Wei et al. 1997), or with individual honeydew sugars. We also describe the development of sticky cotton lint over time in fields infested with sweetpotato whiteflies and cotton aphids.

#### Sweetpotato Whitefly Honeydew Production

All sweetpotato whitefly life stages, except eggs, produce honeydew. Significant differences in quality and quantity occur between honeydew excreted by adult males and females and between the different nymphal stages. Adult females produce more honeydew drops (64 per day) compared with males (26 per day) (Henneberry et al. 2000a), and the honeydew excreted by female insects is more complex than that secreted by males (Hendrix 1999) (table 2). Honeydew produced by sweetpotato whitefly females has more glucose, fructose, trehalulose, and total measured honeydew sugars than that produced by males. Amounts of melezitose and sucrose in honeydew produced by females and males appear similar.

There are four sweetpotato whitefly nymphal stages. Development from egg hatch to adult emergence takes about 12 days (at 26.7 °C, 14:10 L:D) (Henneberry et al. 2000a). Honeydew production begins the first day of nymphal life. The size of honeydew drops (visual observation) and total honeydew production increase with increasing nymphal instar (table 3; also see Costa et al. 1999). First- and second-instar nymphs may produce more honeydew drops than third- and fourth-instar nymphs, but the drops secreted by the earlier stages are smaller. The trehalulose content of nymphal honeydew is variable but in general increases with nymphal age. Lesser amounts of melezitose, glucose, sucrose, and fructose are produced compared with trehalulose. When compared with other instars, fourth-instar nymphs produce larger amounts of glucose and fructose than first- and second-instar nymphs and larger amounts of trehalulose and total sugar.

#### Sweetpotato Whitefly Honeydew Sugar Relationships to Sticky Cotton

Aqueous solutions of the major sweetpotato whitefly honeydew sugars (11 percent glucose, 11 percent fructose, 17 percent melezitose, 16 percent sucrose, and 45 percent trehalulose) in mixtures or rehydrated lyophilized honeydew extracted from contaminated lint were sprayed with an air brush sprayer on 10-g samples of “clean cotton.” Non-honeydew-contaminated “clean cotton” was obtained from cotton grown in areas not infested with whiteflies or aphids. Solutions delivered 5, 10, 15, 20, 25, 30, or 35 mg of sugar mixture or rehydrated honeydew per gram of lint. SCT spots increased with increasing concentrations of the sugar mixtures (figure 1,  $r^2 = 0.90$ ) or rehydrated lyophilized honeydew lint extracts (figure 1,  $r^2 = 0.95$ ). The solutions contained individual sugars in the same ratio as in excreted honeydew (Hendrix et al. 1992, Henneberry et al. 2000a). A 4 percent isopropyl alcohol elution of honeydew from a powdered charcoal-diatomaceous-earth column (Whistler and Durso 1950) contains mostly disaccharides and trisaccharides; a 6 percent elution contains mostly tetrasaccharides and pentasaccharides (Wei et al. 1997; see also figure 2). Aqueous solution sprays of the 4 percent and 6 percent fractions containing 10, 20, 30, or 40 mg/g lint also caused increasing lint stickiness with increasing amounts of the fractions in the spray solutions (table 4).

These large oligosaccharides constitute more than 16 percent of the sugars in the honeydew sample used (Wei et al. 1996). The results suggest that these complex sugars, some as yet unidentified, also

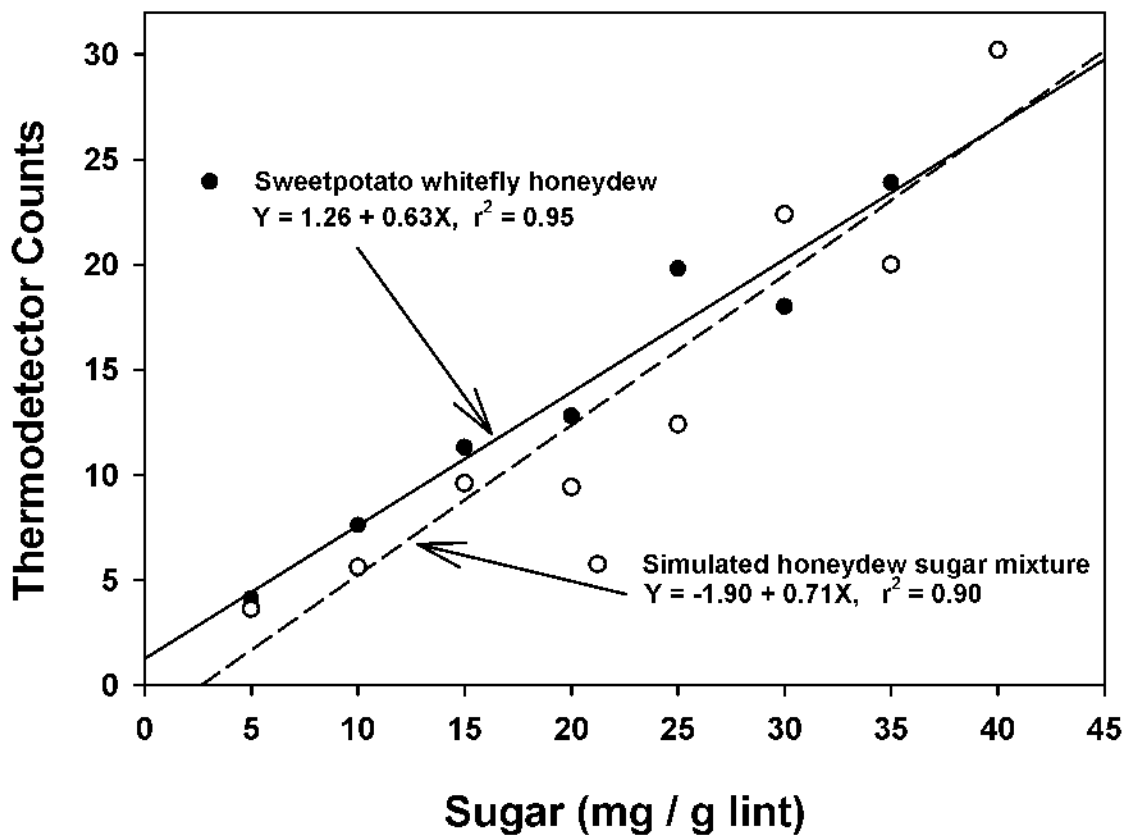


Figure 1. Mean numbers of SCT spots for cotton lint sprayed with sweetpotato whitefly honeydew or a laboratory simulated honeydew sugar mixture (11% glucose, 11% fructose, 17% melezitose, 16% sucrose, and 45% trehalulose).  $F$  for honeydew = 98.07;  $df = 1,6$ ;  $P \leq 0.01$ .  $F$  for sugar mixture = 56.01;  $df = 1,6$ ;  $P \leq 0.01$  (modified from Henneberry et al. 2000a).

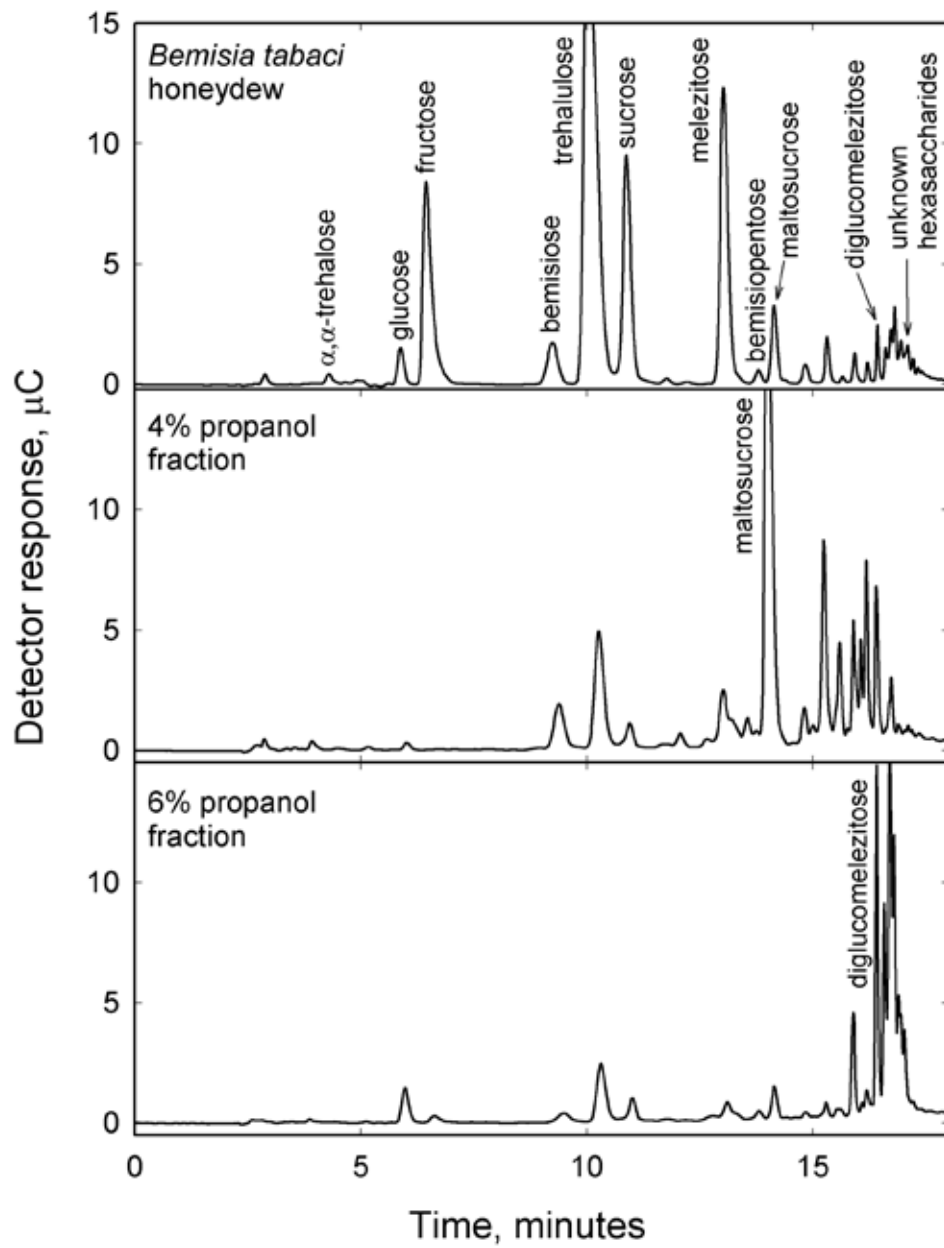


Figure 2. Some known sugars in *B. tabaci* honeydew and sugars eluted from a charcoal-diatomaceous earth column with 4% and 6% isopropanol (Modified from Wei et al. 1997).

contribute to the sticky cotton problem. Commercially obtained glucose, fructose, sucrose, and melezitose and trehalulose (93 percent pure syrup)\* in solutions individually sprayed on clean cotton lint produced different levels of lint stickiness (figure 3). Trehalulose, sucrose, and melezitose produced higher levels of stickiness compared with the same amounts of fructose or glucose, which is in agreement with the results of Miller et al. (1994).

### **Development of Sweetpotato Whitefly Populations and Sticky Cotton in the Field**

In the field, increased populations of sweetpotato whiteflies, honeydew sugars, and sticky cotton (Henneberry et al. 1995, 1996, 1998a,b) have been positively correlated to increased minicard and SCT stickiness measurements. Typically in the southwestern United States, sweetpotato whitefly adults begin to appear on cotton in late June and early July; and when uncontrolled, populations may increase to action threshold levels (5 to 10 per leaf), signaling the need for treatment, by mid July (figure 4). Nymph populations follow a similar pattern of increase but 2 to 3 weeks later than the adult population. Numbers of sweetpotato whitefly eggs, adults, and nymphs on cotton leaves are highly correlated (Henneberry et al. 1995).

Cotton plant phenology and the development of open bolls with lint exposed to increasing sweetpotato whitefly populations are important factors in sticky cotton development. For upland cotton planted about April 7-14 in most of the southwestern U.S. cotton-growing areas, mature bolls typically begin to open between August 18 and 22 (figure 4). For cotton boll development as shown in the figure, about 6 percent of the total seasonal numbers of bolls opened by late August, and openings increased to a peak in the first week of September. Numbers of open bolls decline thereafter, and 98 percent of all the bolls opened by September 15. This is a generalized description of cotton boll phenology and may vary slightly from year to year depending on planting dates and weather, particularly heat unit accumulation.

Nonetheless, the development of sticky cotton during the growing season is an accumulative process, with the lint in the earliest open bolls exposed to potential

deposition of honeydew. Thereafter, opening bolls are exposed to increasing numbers of whiteflies producing honeydew but for shorter periods. Quantifying the accumulated effect is complicated because the honeydew-producing insects generally increase in population density as the season progresses and higher percentages of the total boll production are mature and open. An extremely critical period is that between mid September and defoliation and harvest, when 98 percent or more of the total boll crop is open and exposed to honeydew deposition. For the open-boll curve shown in figure 4, the regression of SCT counts (not shown on the graph) for lint from seed cotton samples taken after 8, 15, 22, and 29 days of exposure was highly significant ( $y = -2.35 + 0.67 x$ ;  $r^2 = 0.75$ ).

The honeydew sugars produced by sweetpotato whiteflies, trehalulose and melezitose, generally increase on cotton with increasing days of lint exposure of open bolls (figure 4). Accumulated numbers of adults from the time of earliest open bolls to the end of the first fruiting cycle result in increasing amounts of trehalulose ( $y = -1.80 + 0.03 x$ ;  $r^2 = 0.95$ ) and melezitose ( $y = -0.15 + 0.005 x$ ;  $r^2 = 0.67$ ), as do accumulated numbers of nymphs for the same periods ( $y = 0.04 + 0.03 x$ ;  $r^2 = 0.97$  for trehalulose;  $y = 0.16 + 0.005 x$ ;  $r^2 = 0.68$  for melezitose). Accumulation of trehalulose ( $y = -0.29 + 8.25 x$ ;  $r^2 = 0.85$ ) and melezitose ( $y = -5.83 + 40.66 x$ ;  $r^2 = 0.97$ ) on harvested lint results in a significant increase in the numbers of SCT spots.

Late-season rainfall after boll opening is another important factor in the sticky cotton problem. SCT spots and honeydew sugars on cotton lint decrease following rainfall (Henneberry et al. 1995, 1996, 1998a,b). This effect is shown in figure 5. Rainfall of 0.11, 0.20, 0.31, and 0.31 cm occurred on days 23, 29, 34 and 49, respectively, after boll opening began. These rainfalls kept whitefly populations and whitefly-produced trehalulose and melezitose—as well as SCT spots—at low levels through October 15, 27 days after 94 percent of the bolls that would open for the season had opened.

The risk of extending the cotton season when sweetpotato whitefly populations are an issue is illustrated in figure 5. Increased late season nymph and adult populations during the 5-day period following October 15 resulted in increasing amounts of trehalulose and melezitose on lint with resulting increase in SCT spots; spot count averaged about 7.0

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\* Purified to an off-white powder by the methods of Hendrix and Peelen (1987).

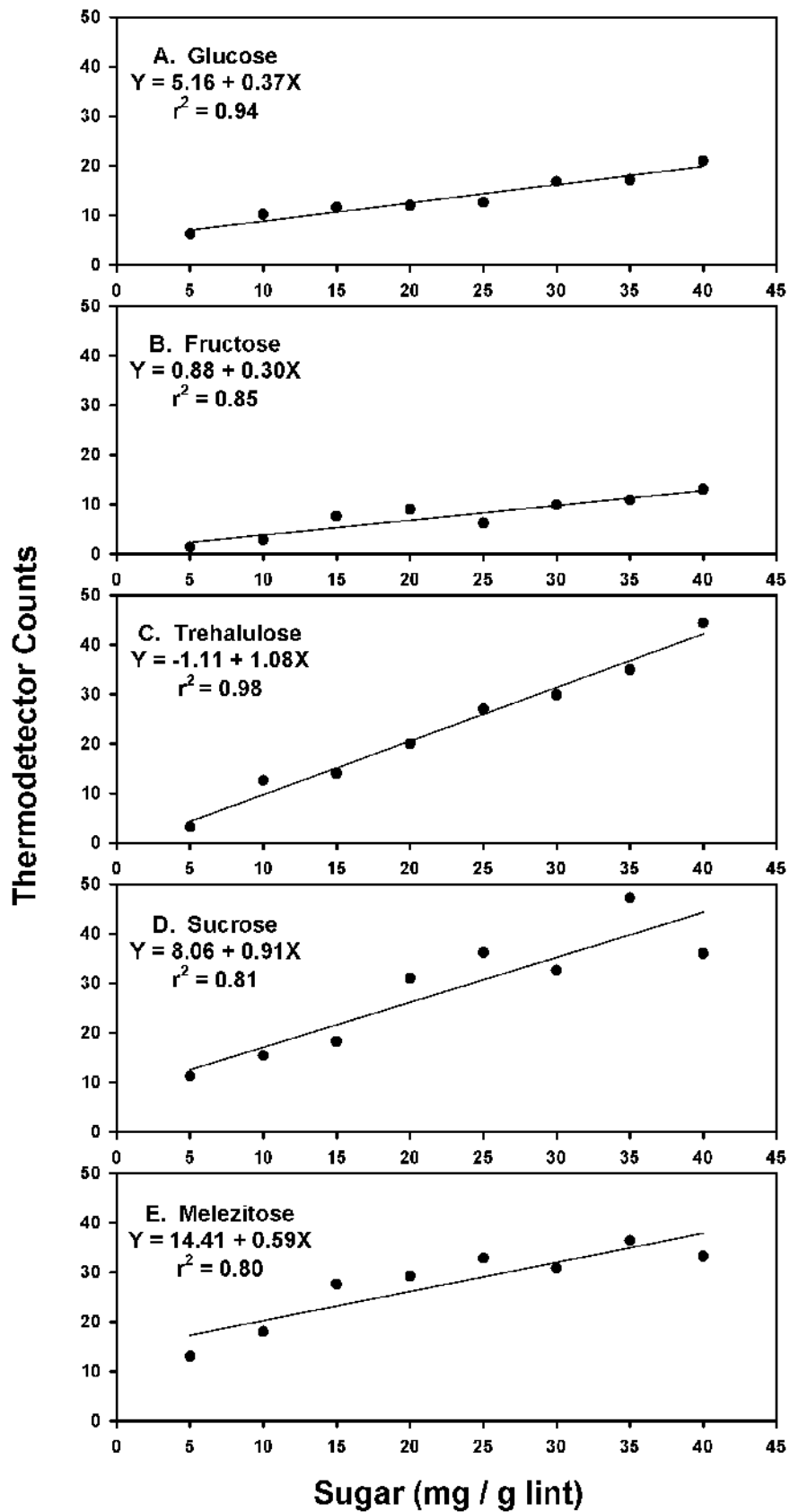


Figure 3. Mean numbers of SCT spots for cotton lint sprayed with individual honeydew sugars at different concentrations.  $F$  values = 94.85 for glucose, 33.56 for fructose, 325.55 for trehalulose, 25.76 for sucrose, and 23.61 for melezitose; for all cases  $df = 1,7$  and  $P \leq 0.01$  (modified from Henneberry et al. 2000a).



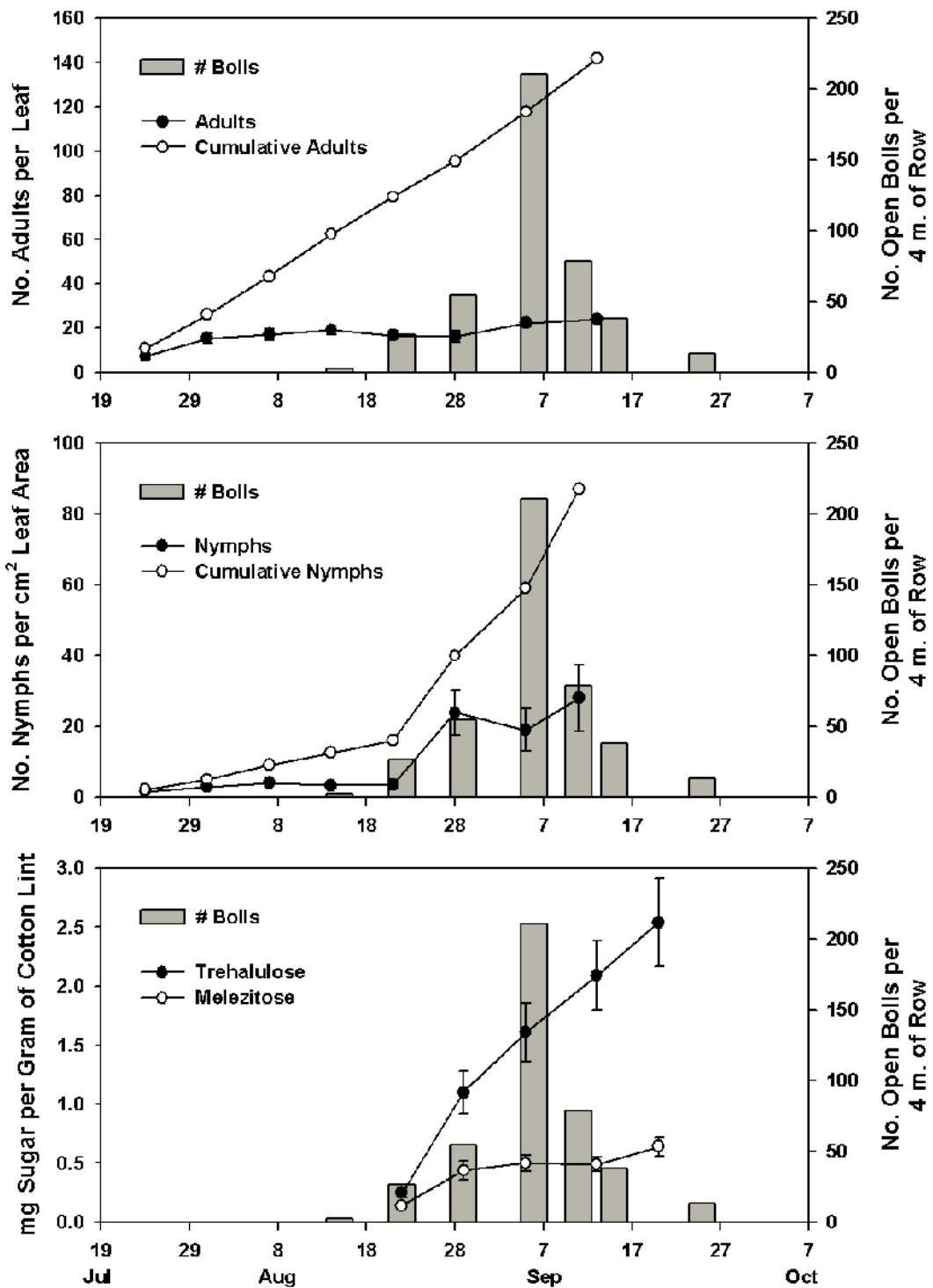


Figure 4. Mean numbers counted on identified days and accumulated numbers of sweetpotato whitefly adults per leaf turn and nymphs per leaf disk, numbers of open cotton bolls, and occurrence of the insect sugars trehalulose and melezitose on cotton lint (modified from Henneberry et al. 1998a,b).

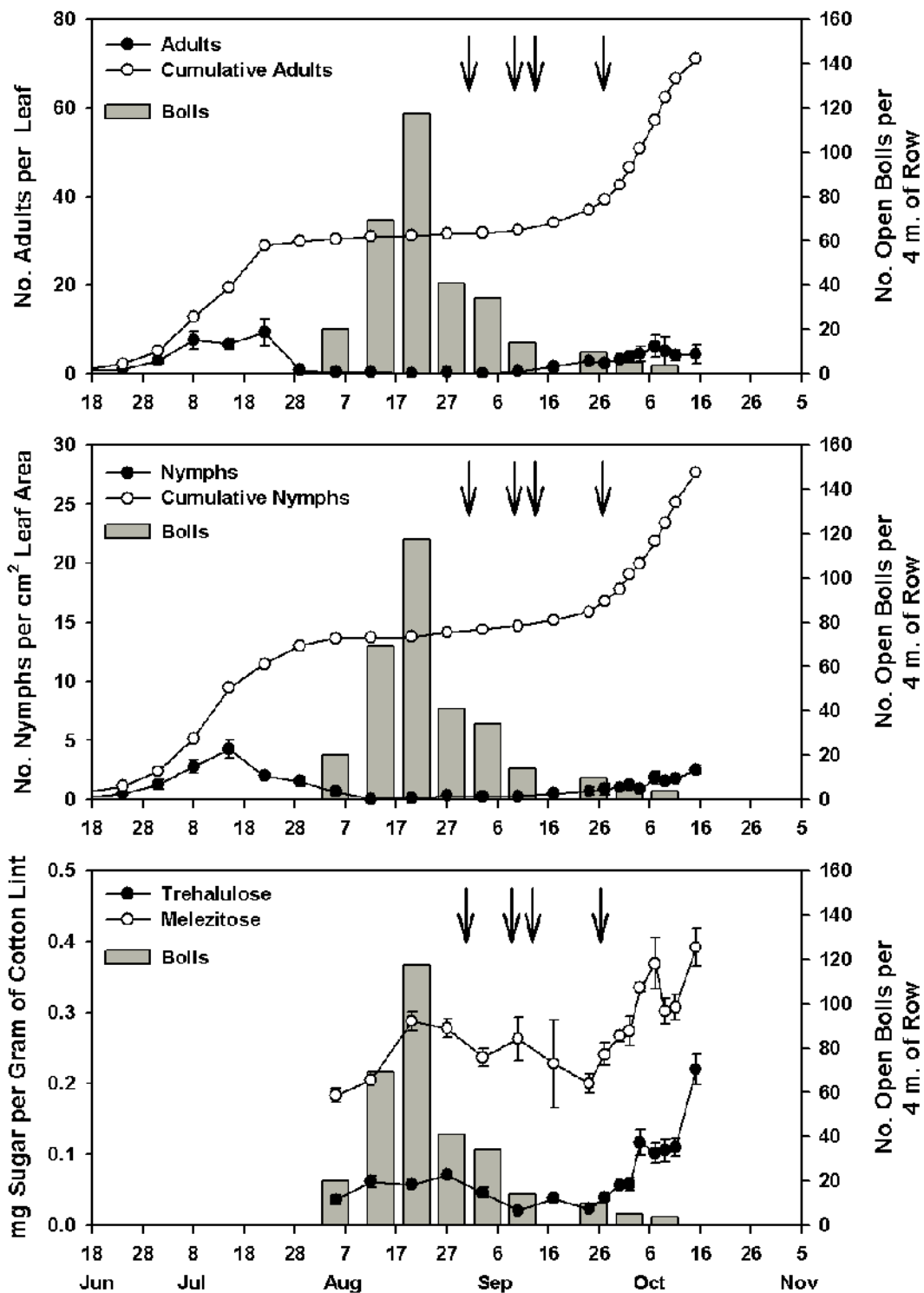


Figure 5. Mean numbers counted on identified days and accumulated numbers of sweetpotato whitefly adults per leaf turn and nymphs per leaf disk, numbers of open cotton bolls, and occurrence of the insect sugars trehalulose and melezitose on lint following rainfalls (arrows) (modified from Henneberry et al. 1998a,b).

on October 30. This is near the threshold (SCT spots of 5.0) that requires some action to protect from further honeydew accumulation (Brushwood and Perkins 1993). The accumulated number of adults during that period was significantly related to lint trehalulose ( $y = 0.11 + 0.004 x$ ;  $r^2 = 0.78$ ) and melezitose ( $y = 0.09 + 0.004 x$ ;  $r^2 = 0.71$ ) content. Accumulated nymph relationships to lint trehalulose and melezitose content were  $y = -0.17 + 0.01 x$ ;  $r^2 = 0.83$ , and  $y = 0.04 + 0.01 x$ ;  $r^2 = 0.71$ , respectively.

The mechanism(s) involved in lint stickiness reduction following rainfall is partially explained by the removal of honeydew by rain. Seed cotton moisture can increase dramatically following rainfall, whereas trehalulose and melezitose decrease (Henneberry et al. 1999). Increasing seed cotton lint moisture following rainfall may stimulate microbial activity, accounting for the degradation in sugars (Hendrix et al. 1993). However, in our studies rapid reductions in sugars (68 to 100 percent within 5 hours) following a rainfall suggests that the major cause of the stickiness reduction is rainfall dissolving sugars followed by runoff from contaminated lint. Microbial activity is not completely ruled out as a cause of stickiness reduction (Elliott 2002). However, under laboratory conditions cotton stickiness did not decline for several days following increased seed cotton moisture content, and seed cotton moisture must be maintained at 10-12 percent for microbial activity to effect detectable sugar degradation (Henneberry et al. 1997).

### **Cotton Aphid Honeydew Production**

Cotton aphids in the southern United States reproduce viviparously throughout the year (Slosser et al. 1992). They have four nymphal stages, each stage lasting about a day, but development can take longer at low temperatures (Akey and Butler 1989, Henneberry et al. 2000b). Nymphs on days one, two, three, and four of their life (first to fourth instars) produce an average of 14, 12, 8, and 8 honeydew drops per day, respectively (Henneberry et al. 2000b). The total amount produced of glucose, fructose, trehalulose, sucrose, and melezitose combined was 4.33  $\mu\text{g}$  in the first nymph stage, 4.36  $\mu\text{g}$  in the second, 3.88  $\mu\text{g}$  in the third, and 2.99  $\mu\text{g}$  in the fourth.

### **Cotton Aphid Honeydew Sugar Relationships to Sticky Cotton**

For the cotton aphids feeding on cotton, melezitose is typically the dominant insect-produced sugar, with

lesser amounts of trehalulose (Hendrix et al. 1992, Hendrix 1999). However, the melezitose content of cotton aphid honeydew does exhibit considerable variation, and in some instances melezitose occurs in only small amounts (D.L. Hendrix, 1999, unpublished data). Sugars commonly found in both sweetpotato whitefly and cotton aphid honeydew are fructose, glucose, and sucrose. Cotton lint exposed to cotton aphids in the laboratory show increasing numbers of SCT spots with increasing numbers of days of exposure (figure 6a,  $r^2 = 0.93$ ). SCT spots increase with increasing amounts of glucose ( $r^2 = 0.53$ ), fructose ( $r^2 = 0.81$ ), sucrose ( $r^2 = 0.69$ ), and the total of all sugars ( $r^2 = 0.72$ ) extracted from aphid-honeydew-contaminated lint. Similar results were observed for days of lint exposure in the field (figure 6b,  $r^2 = 0.55$ ) and increasing numbers of SCT spots on cotton lint with increasing amounts of cotton aphid honeydew sugars (glucose  $r^2 = 0.81$ , sucrose  $r^2 = 0.79$ , melezitose  $r^2 = 0.70$ , and total of all sugars  $r^2 = 0.77$ ). In north Texas cotton fields infested with cotton aphids, number of SCT spots increased proportionally to the increasing amounts of melezitose (Slosser et al. 2002). In cotton from these fields, a melezitose concentration of about 90  $\mu\text{g}$  per gram of lint was associated with a threshold number of SCT spots (10) (Brushwood and Perkins 1993) that suggest the need for action to prevent additional sugar accumulation that could be of economic concern.

### **Discussion**

Aqueous solutions of honeydew extracted from baled cotton lint and resprayed on noncontaminated cotton suggest that about 6 mg of honeydew per gram of cotton resulted in a thermodetector count corresponding to lightly sticky cotton. Correcting for a spray application efficiency of about 58 percent, a thermodetector count of 5 was reached at about 3.8 mg of honeydew per gram of cotton lint. This is probably only a relative figure since it is highly improbable that the extracted, lyophilized, and water-reconstituted honeydew exhibits the identical physical and chemical characteristics of honeydew excreted by whiteflies. For example, atomizer-produced drops are larger than those produced by insects and drop size is an important factor in stickiness measurement (Henneberry et al. 2000a).

Several of the sugars found in honeydew, such as fructose, glucose, and sucrose, also occur naturally as physiological sugars in the growing cotton fibers. The effects and degree of contribution to the sticky

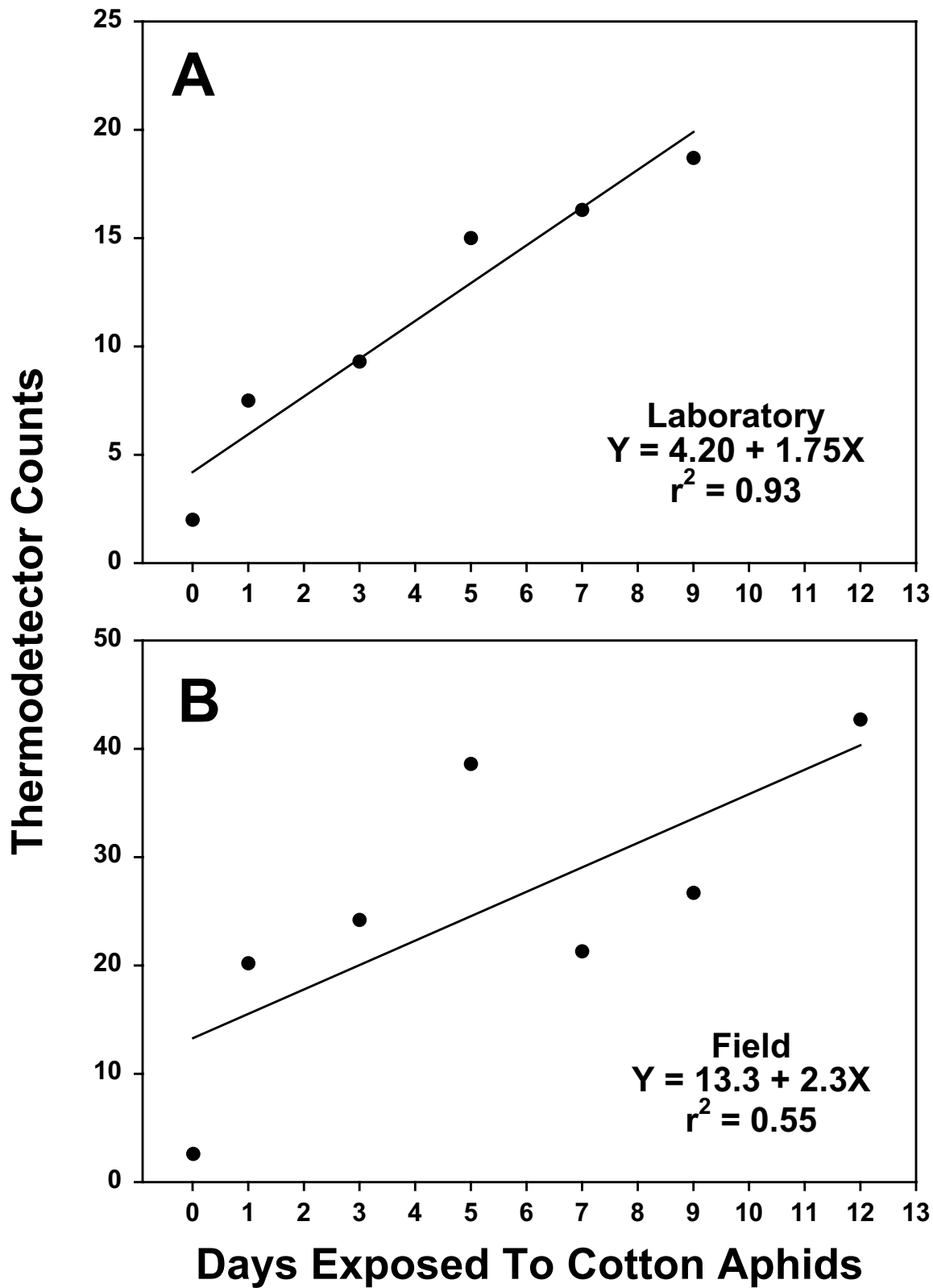


Figure 6. Mean numbers of SCT spots on cotton lint following exposures for different numbers of days to cotton aphids feeding on cotton lint in the laboratory (A) and in the field (B). Controls (0) were unexposed lint samples. In the laboratory  $F = 56.77$ ;  $df = 1,5$ ;  $P \leq 0.02$  in the field,  $F = 6.22$ ;  $df = 1,5$ ;  $P \leq 0.05$  (modified from Henneberry et al. 2000b).

cotton problem from physiological sugars cannot be readily separated from the effects of honeydew sugars. Thermometer counts of individual sticky spots measure the overall contribution of all sugar components from lint. However, the vast majority of stickiness in cotton fibers is caused by honeydew contamination, not physiological sugars (Hector and Hodkinson 1989).

A more complete understanding of the biology and ecology of the honeydew-producing insects and interactions with their hosts is essential to a complete understanding of the honeydew sticky cotton relationships and may lead to identification of long-term ecological approaches to managing honeydew-producing insects. The reasons for differences in quality and quantity of honeydew sugars produced by male and female sweetpotato whiteflies and between adults and nymphs remains unknown, but may be important biologically. A partial explanation may be inferred from the work of Isaacs et al. (1998) who found that trehalulose production by *B. tabaci* more than doubled when feeding on water-stressed compared with non-water-stressed melons. Also, Hendrix (1999) found that sugars within the bodies of whiteflies feeding on water-stressed plants were significantly different from those in insects feeding on well-watered plants. Thus, changes in plant physiology may be reflected in insect feeding biology and, hence, honeydew production.

Increasing our knowledge in these areas of pest and host plant interaction has much potential for practical application. For example, water management in cotton culture is a farmer-adopted method of reducing cotton plant stress and sweetpotato whitefly populations (Flint et al. 1996). Other farm practices may also be important in managing the sticky cotton problem. Fewer honeydew drops appear to be produced by nymphs while feeding on high-nitrogen-fertilized seedlings compared with nymphs feeding on low-nitrogen-fertilized seedlings (Blua and Toscano 1994). Nymphs feeding on plants supplied high levels of nitrogen initiate honeydew production earlier (2 days) than nymphs feeding on plants fertilized with low or medium amounts of nitrogen.

Hendrix and Salvucci (1998) and others (Salvucci et al. 1997) have suggested that the larger saccharides (trehalulose, melezitose, and larger oligosaccharides) may play a significant role in the physical and chemical

characteristics of honeydew and in the osmotic regulation of the insect's body fluids. For aphids, conversion of sucrose to oligosaccharides has been suggested as a mechanism to allow these insects to adjust to phloem sap osmotic concentrations to prevent water loss in the hemolymph (Kennedy and Stroyan 1959, Fisher et al. 1984, Rhodes et al. 1997, Ashford et al. 2000). However, differences in amounts and types of sugars produced by the two sexes may be partially explained by differences in the sizes of male and female *B. tabaci*. Females weigh nearly 2.5 times (average 51  $\mu\text{g}$ ) as much as males (average 21  $\mu\text{g}$ ) (Isaacs et al. 1998). In addition, egg production by females may require a different level of osmoregulation than is necessary in male insects (Castañé and Savé 1993).

The carbohydrate aspects of the sweetpotato whitefly cotton host interaction is complex and may significantly reflect biological and ecological adaptations of the insect. Salvucci et al. (1997) proposed that trehalulose is synthesized for excretion by sweetpotato whitefly feeding on cotton when carbon input from sucrose is in excess of metabolic needs. Isaacs et al. (1998) found greater carbohydrate concentrations in phloem sap from water-stressed melons *Cucumis melo*, compared to phloem sap from non-water-stressed melons. They also found that whiteflies feeding on the higher carbohydrate phloem sap produced significantly more trehalulose than when feeding on lower carbohydrate sap. These authors speculated on biological advantages that may be afforded by having the ability to control internal osmotic hemolymph relationships in diverse plant-ecological systems. An understanding of this interaction and knowledge of the total carbohydrate composition of honeydew may help in developing approaches to control or chemical (or enzymatic) methods to reduce stickiness in harvested cottons by designing chemistry or enzymatic methods specifically tailored for the removal of known honeydew sugars (Hendrix et al. 1993, 1996, 2001).

Water management of late-season cotton and timing of defoliation and harvest are critical activities when sticky cotton is a possibility. Lint in bolls opening during the entire first fruiting cycle may be exposed to low-level whitefly populations and escape honeydew contamination. Delaying defoliation and harvest risks exposing open bolls to increased late-season whitefly populations, particularly following termination of insecticide use, and cotton stickiness can develop in a relatively short exposure time. Thus, timing of

defoliant application in relation to the last insecticide protection or the last detectable increase in whitefly population can be an important tool in managing the cotton crop to avoid lint stickiness. For the grower, difficult decisions have to be made. Maximum yields return the highest gross profit. Less than maximum yields with lower gross profit but the potential for equal or higher net profit by avoiding sticky cotton must also be considered. The occurrence of fortuitous rains and effective insecticide control may protect the first

cotton fruiting cycle from stickiness. The decision late in the season to extend the growing season under these conditions would be appealing but has the obvious risk of exposure to increased whitefly populations, increasing the risk of changing the crop from nonsticky to lightly sticky. Discounts of 10 percent or more on honeydew-contaminated lint, losses from reduced cotton ginning efficiency, and increased costs of machinery maintenance (Hector and Hodgkinson 1989) need to be factored into such a decision.

**Table 1. Mean numbers of honeydew drops and amounts of honeydew sugars produced per cotton aphid nymph per day**

[Means of 42 aphids. Means in a column not followed by the same letter are significantly different. Method of least significant differences  $P \leq 0.05$ ]

Nymph age	Number of drops	Sugar					Total
		Glucose	Fructose	Trehalulose	Sucrose	Melezitose	
days		.....µg .....					
1	14.30 a	0.28 a	0.51 a	0.05 a	3.42 a	0.07 a	4.33 a
2	11.90 ab	0.34 a	0.56 a	0.03 a	3.30 a	0.13 a	4.36 a
3	7.70 b	0.33 a	0.51 a	0.02 a	2.97 ab	0.04 a	3.88 ab
4	7.60 b	0.28 a	0.51 a	0.06 a	2.11 b	0.04 a	2.99 b

Modified from Henneberry et al. 2000b.

**Table 2. Mean longevity, numbers of honeydew drops, and amounts of honeydew sugars produced per sweetpotato whitefly adults during their life span at 26.7 °C**

[Means of 8 replications, 2 adults per replication. Means in a column not followed by the same letter are significantly different. Method of least significant differences  $P \leq 0.05$ ]

Sex	Longevity days	Number of drops	Sugars					Total
			Glucose	Fructose	Trehalulose	Sucrose	Melezitose	
Males	22.9 a	594.3 b	1.81 b	2.09 b	3.18 b	10.62 a	1.36 a	19.05 b
Females	29.7 a	1916.9 a	3.98 a	6.97 a	48.04 a	7.26 a	2.37 a	68.63 a

Modified from Henneberry et al. 2000a.

**Table 3. Mean numbers of honeydew drops and weight of individual honeydew sugars produced per sweetpotato whitefly nymphal stage during development**

[Means of 15 replications, 2-6 nymphs per replication for a total of 52 nymphs. Means in a column not followed by the same letter are significantly different. Method of least significant differences  $P \leq 0.05$ ]

Nymphal Instar	Number of drops	Honeydew sugars produced per nymph						Total
		Glucose	Fructose	Trehalulose	Sucrose	Melezitose		
First	185.3 a	0.11 bc	0.10 c	0.12 b	0.50 a	0.20 a	1.04 b	
Second	144.5 a	0.06 c	0.14 bc	0.36 b	0.14 a	0.10 a	0.78 b	
Third	71.2 b	0.16 ab	0.30 ab	0.43 b	0.26 a	0.12 a	1.26 b	
Fourth	47.4 b	0.23 a	0.35 a	0.84 a	0.52 a	0.32 a	2.26 a	

Modified from Henneberry et al. 2000a.



**Table 4. Mean numbers of SCT spots from cotton lint sprayed with 4% or 6% isopropyl alcohol fractions of whitefly honeydew**

[Means (five replications) in a row not followed by the same letter are significantly different.  $F = 11.36$ ;  $df = 4, 19$ ;  $P \leq 0.05$ . Mean separation by method of least significant differences]

Isopropyl alcohol fraction	Sugar application (mg/g lint)				
	0*	10	20	30	40
4%	1.50 c	9.75 b	14.00 ab	18.75 a	19.75 a
6%	2.75 b	11.00 ab	15.25 a	17.25 a	19.00 a

Modified from Henneberry et al. 2000a.

\* Water.

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## Chapter 6

### **Biology, Ecology, and Management of Sweetpotato Whiteflies on Cotton**

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The sweetpotato whitefly was first described in 1889 and called the tobacco whitefly. It was for many years considered a tropical-subtropical pest with its distribution delimited by latitudes of about 30° north and south of the Equator. Its geographical range has extended; the species is now globally distributed and found on all continents except Antarctica (Martin 1999, Martin et al. 2000). Evolutionary relationships indicate that the sweetpotato whitefly may have originated in tropical Africa and that introductions into the Neotropics and southern North America are quite recent (Campbell et al. 1996). Other evidence suggests that it may be native to India or Pakistan, where the greatest diversity of the species' parasitoids have been found, a criterion that has been considered a good indication of a genus epicenter (Brown et al. 1995). Numerous synonyms and biotypes have been identified throughout the world (see Perring 2001).

Sweetpotato whiteflies became a serious pest of cotton in the late 1920s and early 1930s in northern India (now part of Pakistan) (Misra and Lamba 1929, Husain and Trehan 1933). Subsequently, severe infestations on cotton were recorded in the Sudan and Iran (1950s), El Salvador (1961), Mexico (1962), Brazil (1968), Turkey (1974), Israel (1976), Thailand (1978), Arizona and California, U.S.A. (1981), and Ethiopia (1984) (Basu 1995). Insecticide use in many cases resulted in the development of resistance (chapter 9) and a general failure of control efforts. In the Sudan, Dittrich et al. (1990) attributed part of the problem to the ability of insecticide-resistant individuals to increase their oviposition rates when under insecticidal stress (hormoligosis). In contrast, Eveleens (1983) considered suppression of aphelenid parasitoids with broad-spectrum insecticides as a major cause of the outbreaks. Castle (1999) reappraised the Sudan situation and suggested that the influence of agricultural intensification of cotton acreage, increased fertilizer and other production technology, later planting dates, and overuse of insecticides were factors contributing to the increasing importance of sweetpotato whiteflies. It is likely that all of these factors have affected population outbreaks. In cotton, the insect causes

direct feeding damage that reduces yields, transmits viruses causing cotton leaf crumple and cotton leaf curl disease (Brown et al. 1995), and contaminates lint with honeydew (Hector and Hodkinson 1989).

Cotton leaf crumple virus (CLCrV) in California resulted in cotton yield reductions of 41 to 81 percent in the mid 1960s (Van Schaik et al. 1962), and major epidemics occurred in Arizona from 1981 to 1984 (Brown and Nelson 1984). Cotton leaf curl virus (CLCuV) has been known for many years in Pakistan (Mahmood 1999), but rapid spread of the disease started in 1988, when 24 ha was known to be infected. Infection increased to about 121,458 ha in 1992, reducing cotton production by 30-40 percent in 1993 and 1994. Estimates of losses from 1994 to 1999 were about 7.4 million cotton bales valued at \$4.98 billion (Mansoor et al. 1999). In India, CLCuV was first detected from Sri Gangenagar in 1993 and Punjab in 1994 (Singh et al. 1999). At present, it is widespread over the entire northern cotton-producing zone of India. In the Punjab, cotton production in 1998 had decreased 75 percent from 1990 (Singh et al. 1999). Cotton leaf curl is suggested as a major factor in the decline.

Except for the effect of cotton leaf crumple in the western United States and cotton leaf curl in Pakistan and India, the most important economic issues associated with high sweetpotato whitefly populations concern sticky cotton. Nymphs and adults feeding on cotton excrete a mixture of sugars (Hendrix et al. 1992) called honeydew. Honeydew-contaminated cotton lint is sticky and also serves as a substrate for sooty molds that discolor the lint. Sticky cotton adheres to machinery in textile mills and interferes with processing. Sticky cotton reduces harvesting and ginning efficiency (Johnson et al. 1982, Hector and Hodkinson 1989). Sticky cotton also may contain leaf trash and dirt that has been reported to cause health problems for textile mill workers (Ayars et al. 1986).

Sticky cotton is a serious problem in many cotton production areas in the world (Strolz 1992). Upwards of 10 percent of the lint value may be lost (Hector and Hodkinson 1989). Between 1994 and 1998, Arizona, California, and Texas cotton growers spent about \$154 million (Ellsworth et al. 1999) to control sweetpotato whiteflies and prevent cotton lint stickiness. The degree of lint stickiness is directly related to the magnitude of infestations, which in turn is influenced by the efficiency of population management. Most control efforts are insecticide-based, but the most successful

management is facilitated by an understanding of the biology and ecology of the species and melding of chemical, biological, cultural, and other control tactics.

In this chapter, we briefly review the biology and ecology of the insect and then discuss developments that have led to efficient systems for its management on cotton.

## **Biology and Ecology**

Several excellent reviews have summarized the biology, ecology, and population dynamics of sweetpotato whiteflies (Horowitz 1983, Butler and Henneberry 1986, Butler et al. 1986, 1989, Gerling and Ohnesorge 1986, Byrne and Bellows 1991, Henneberry and Castle 2001), and readers are urged to consult these for more detail.

### **Development, Survival, and Reproduction**

Time to complete immature stage development varies as a function of temperature (tables 1 and 2) and can also be affected by the host plant. Total development times of eggs and the four nymphal stages in the field may vary greatly (14 to 107 days). Egg development in the laboratory takes from 5 days at 34.7 °C to 23 days at 15.4 °C (El-Helaly et al. 1971, Butler et al. 1983, Von Arx et al. 1983, Wagner 1995). Nymph development times in the laboratory vary from 10.7 days at 27.5 °C to 36.3 days at 17.7 °C (Enkegaard 1993, Wagner 1995). Several researchers have demonstrated the effects of host plants on development times (Coudriet et al. 1985, 1986, Wang and Tsai 1996, Tsai and Wang 1996). Differences in development times of as much as 10 days have been observed on different hosts at similar temperatures.

Egg mortality in the laboratory varies from 3.6 to 9.2 percent at temperatures from 17.4 to 34.7 °C (Wagner 1995, Tsai and Wang 1996, Wang and Tsai 1996). Nymph mortality at temperatures between 20 and 32 °C was 17-28 percent, 2-16 percent, 3-14 percent, and 2-24 percent for 1st, 2nd, 3rd, and 4th instars, respectively, on a wide range of hosts (Powell and Bellows 1992, Wang and Tsai 1996, Tsai and Wang 1996). Field estimates of mortality from life table studies in cotton indicate that both eggs and nymphs are subject to mortality from many factors, with total survival of immatures averaging just over 6 percent (Naranjo 2001). Adult males in the laboratory have been observed to live 8-10 days at 16-32 °C and females 10-35 days at 14-32 °C (El-Helaly et al.

1971, Butler et al. 1983, Enkegaard 1993). Under field and insectary conditions, the range of longevity is considerably greater, depending on the time of year, with male longevity ranging from 6 to 34 days and female longevity from 15 to 55 days under temperatures ranging from 12.7 to 26.5 °C (Avidov 1956).

Adults are small (females 1.1-1.2 mm long) yellow-bodied insects. Males are slightly smaller than females. Adults have paired white wings that form an inverted V-shape covering the thorax and abdomen. Reproduction is both sexual and parthenogenic; unfertilized eggs produce only males. Adults emerge between 8:00 a.m. and noon through a T-shaped fissure on the dorsum of the last-stage nymph integument (Husain and Trehan 1933, Azab et al. 1969, Butler et al. 1983). Adults often remain near the pupal case for 10 to 20 minutes following emergence to spread and dry their wings (Avidov 1956). Males and females are sexually immature at emergence (Li et al. 1989). Males begin courting females 10-24 hours after emergence. The period until egg-laying may range from 1 to 22 days depending on temperature under field and insectary conditions (Avidov 1956) and 2 to 5 days under laboratory conditions.

Females firmly embed the eggs in leaf tissue with a vertical orientation (Avidov 1956, Buckner et al. 2001). Eggs are elliptically shaped, narrow at the apical end and broadly rotund at the base with a pedicel or stalk. Under field and insectary conditions on cotton, females have been reported to lay 28 to 43 eggs (Husain and Trehan 1933). Egg-laying under controlled temperature laboratory conditions have been highly variable, ranging from 32 to 257 eggs per female over a temperature range of 25.5 to 32.6 °C (Butler et al. 1983, Horowitz 1983, Von Arx et al. 1983, Bethke et al. 1991, Powell and Bellows 1992).

### **Host Plants and Dispersal**

Sweetpotato whiteflies have been reported to have a host range exceeding 500 plant species (Mound and Halsey 1978), and differences in whiteflies' use of the various plant species has long been recognized. In India during the 1920s and 1930s, the insect was intensively studied as a serious pest of cotton, but it was also observed to colonize other crops and wild hosts throughout the year (Husain and Trehan 1933). In other regions, sweetpotato whiteflies have been a pest principally on crops other than cotton such as vegetables in Israel (Avidov 1956), soybeans (*Glycine*

*max* (L.) Merr.) in Brazil (Costa 1965), and cassava (*Manihot esculenta* Crantz) in central Africa (Burban et al. 1992). Also, there are well-documented cases of apparent host specialization among certain sweetpotato whitefly populations (Bird 1957, Burbán et al. 1992).

Sweetpotato whiteflies are multivoltine and have no quiescent or diapause stage; except for the first instar, immature forms are immobile. Therefore, adults reproduce continually throughout the year by moving sequentially among various crop and noncrop host plants. During the winter in Arizona, for example, they are found on vegetables such as broccoli (*Brassica* spp.), cauliflower (*Brassica* spp.), and lettuce (*Lactuca sativa*) and on various winter weeds (Watson et al. 1992, Butler and Henneberry 1993). Late winter and early spring hosts include cantaloups, vegetables, and weeds. Cotton is the most abundant summer host, and fall cantaloups (*Cucumis* spp.) and vegetables complete the yearly cycle. Perennial crop and ornamental hosts such as alfalfa (*Medicago sativa* L.), citrus (Rutaceae), *Lantana*, and *Hibiscus* host whiteflies year round (figure 1). Typically, regional populations grow rapidly during the spring and early summer and reach outbreak levels during later summer months, primarily on cotton. Also typical are very low and widely dispersed populations during the colder winter months. This seasonal cycle is highly complex and is governed by a broad array of spatially and temporally varying biotic and abiotic factors. Potential host habitats vary not only spatially but temporally, because many consist of annual plant species or crops that grow during brief periods of the year. Thus, dispersal is a critical factor in sweetpotato whitefly population dynamics.

It has been difficult to quantify and integrate dispersal parameters such as the relative numbers of dispersing whiteflies, their reproductive status, sex ratio, and other biological factors that influence population dynamics (Blackmer and Byrne 1993). Long-range dispersal studies of adults based on aircraft net collections have suggested that vertical convection currents and horizontal air movement concentrate the population (Joyce 1983). Dispersal from heavily infested cotton and melon fields in Arizona to lettuce fields 1.4 to 4.8 km away resulted in average catches of 384 adults per yellow sticky trap in 30-minute sampling periods during peak dispersal activity (Butler and Henneberry 1989). These large-scale movements contributed to the population doubling in lettuce in 7 to 10 days.

### **Crop Production Factors**

As noted, many factors influence sweetpotato whitefly population dynamics in agricultural ecosystems. In cotton, the hirsute leaf character is associated with higher populations than glabrous leaf types. Cohen et al. (1996) hypothesized that lamina trichomes of cotton leaves that originate from elongated epidermal cells overlying leaf veins provide cues to 1st instar crawlers to locate leaf vascular tissue. Access to phloem tissue may be influenced by the geometric relationships of the length of the stylet, the abaxial leaf plan, and the distance of vascular tissue from the point of stylet insertion (Cohen et al. 1996). Stylets of first instar nymphs were reported to be about 80  $\mu\text{m}$  long (Pollard 1955). In one report, nymphs settled within 60 to 80  $\mu\text{m}$  of vascular-bundle-associated epidermal cells, supporting the suggestion that stylet length is a limiting factor in feeding site selection. However, more recent studies suggest that on average, stylet lengths are longer than originally thought and nymphs have access to phloem tissue from almost any point of the underleaf surface (Freeman et al. 2001). Okra-leaf cottons have also been found to support lower populations compared to normal-leaf cottons. The difference between the two types has been attributed to smaller leaf area and more open canopy that provides a less suitable habitat.

Higher sweetpotato whitefly populations have been associated with some crop production inputs such as increased fertilization of cotton (Joyce 1958, Skinner and Cohen 1994) and tomatoes (Sharaf and Batta 1985). Model simulations for sweetpotato whiteflies and water stress resulting in reduced photosynthate suggested that increases in vegetative growth are more favorable for population development (Von Arx et al. 1983). Higher populations have often been reported on water-stressed cotton (Mor et al. 1982, Mor 1983, Flint et al. 1996). Leaf carbohydrate concentrations and honeydew have been shown to be higher in water-stressed melons compared to non-water-stressed melons (Isaacs et al. 1998). The largest differences in honeydew carbohydrate concentrations were for glucose and sucrose, suggesting isomerization of more simple sugars as an osmoregulation mechanism.

### **Weather and Seasonality**

Extremes of weather conditions appear to play an important role in sweetpotato whitefly population dynamics in some areas (Sharaf 1982). Upper temperature thresholds for growth and development are probably greater than 35 °C (Butler et al. 1983, Wagner 1995, Wang and Tsai 1996). Although the effects of

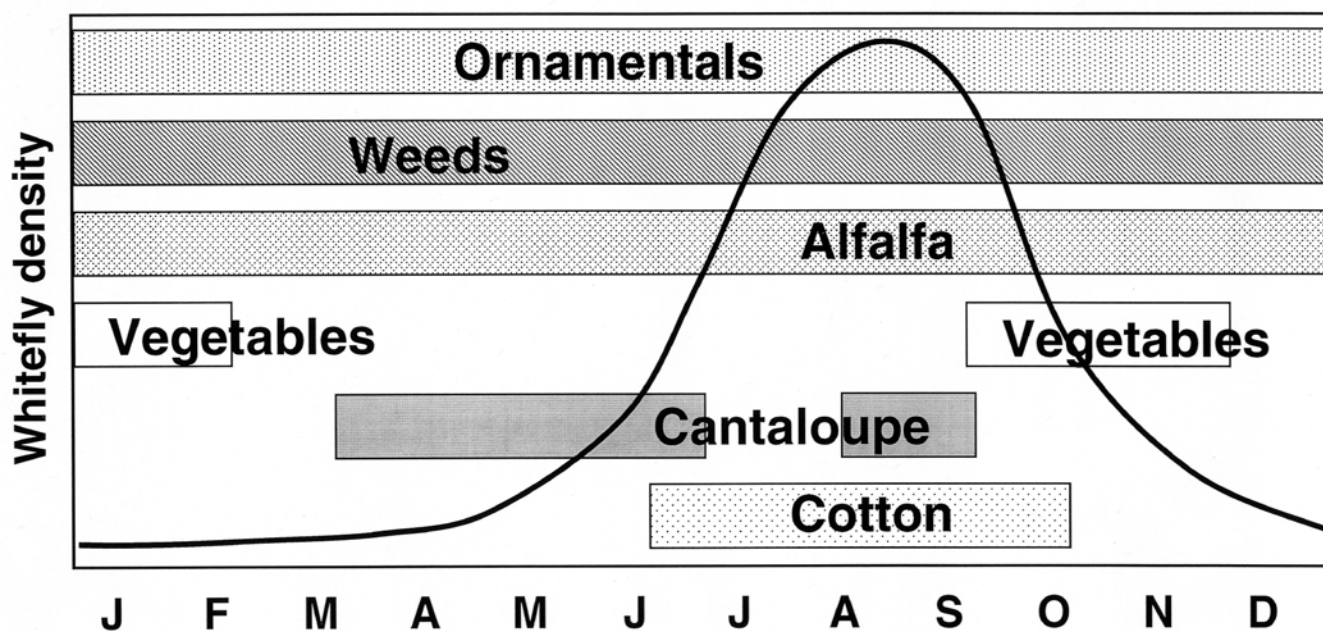


Figure 1. Conceptual diagram of the seasonal cycle numbers of *B. tabaci* in the southwestern United States emphasizing the development of outbreak population numbers during summer months from extremely low population levels during winter.

temperature on life functions is well documented under laboratory conditions, there have been few reports under field conditions except for population reductions following ambient temperatures of 43-45 °C and low humidity (8-17 percent) in cotton fields (Gameel 1969). Rainfall also has an adverse effect on adult populations and egg laying (Peterlin and Helman 1996). Wind is an important factor in dispersal, and crops grown downwind in close proximity to infested crops are more likely to be infested than crops at more distant locations (Watson et al. 1992). Wind and rain can also be an important source of mortality of immature stages by dislodging insects from the plant surface (Naranjo and Ellsworth 1999).

Sweetpotato whiteflies are capable of surviving in mild, temperate climates where protected niches are available or under greenhouse conditions (Simmons and Elsey 1995). Little emphasis has been placed on overwintering survival and effects on subsequent summer population development on cultivated crops. Adult and immature populations decrease dramatically and oviposition is greatly reduced on cultivated crops and weed hosts during fall and winter months. Numerous overwintering hosts have been reported in different areas of the world. In southern California,

overwintering sweetpotato whiteflies and their parasites have been found on *Malva parviflora* L. (a frost-hardy winter weed), *Helianthus annuus* L., *Convolvulus arvensis* L., and *Lactuca serriola*. Sweetpotato whiteflies complete development in winter months on carrot (*Daucus carota* L.), broccoli, squash, eggplant, guar (*Cyamopsis tetragonoloba* (L.) Taub.), guayule (*Parthenium argentatum* A. Gray), alfalfa, and lettuce (Coudriet et al. 1985). At least one generation and a partial second has been observed on lettuce in southern California in winter months. An estimate of the number of empty pupal cases in late autumn indicated that one adult was produced for every 25 mature lettuce leaves, or about 5,000 adults per hectare of lettuce. Empty pupal cases in December on lettuce and reproducing populations on alfalfa, london rocket (*Sisymbrium irio* L.), and alkali mallow (*Sida hederacea* (Doug.) Terr.) have also been reported in the Yuma Valley, AZ (Watson et al. 1992). Low-level egg and nymph populations exist on collards, mustard (*Brassica juncea* (L.)), canola (*Brassica oleracea* var. *acydela* DC), and turnip (*Brassica rapa* L.) during winter in South Carolina (temperature range 9.7 to 16.9 °C) (Simmons and Elsey 1995).

## Natural Enemies

A large number of natural enemies of sweetpotato whiteflies are known worldwide. This information has been summarized in several review articles (Greathead and Bennett 1981, Lopez-Avila 1986, Cock 1994, Nordlund and Legaspi 1996, Faria and Wraight 2001, Gerling et al. 2001). Most recently, Gerling et al. (2001) listed 114 arthropod predators of *B. tabaci* belonging to 9 orders and 31 families. Using immunologically based gut assays, Hagler and Naranjo (1994a,b) have definitively identified 9 predators feeding on sweetpotato whiteflies in Arizona cotton and have since positively identified another 9 species (unpublished) not appearing on the Gerling et al. (2001) list. Gerling et al. further estimated that 34 species of *Encarsia*, 14 species of *Eretmocer*, and several species belonging to the genera *Amitus* and *Metaphycus* attack sweetpotato whiteflies worldwide. Faria and Wraight (2001) list nine described and two undescribed species of fungi that have been shown to occur naturally in *Bemisia* populations worldwide. The most commonly observed fungal pathogens of sweetpotato whiteflies and other whiteflies are *Paecilomyces fumosoroseus* (Wize), *Verticillium lecanii* (Zimmerman), and *Aschersonia aleyrodides* Webber (Lacey et al. 1996).

Despite the large number of potential natural enemies, their overall effect on sweetpotato whitefly population dynamics in agricultural systems is poorly understood. The best examples of the putative suppressive role of extant natural enemies in the field come from studies demonstrating pest resurgence after the use of broad-spectrum insecticides. In commercial-scale studies, Abdelrahman and Munir (1989) demonstrated that applications of broad-spectrum insecticides for control of various pests including sweetpotato whiteflies in Sudan cotton caused reductions in parasitism and predator populations and precipitated economic populations of sweetpotato whiteflies. Similar findings were reported in cotton in Syria (Stam and Elmosa 1990) and Israel (Devine et al. 1998).

Parasitism of 4th instar nymphs as high as 70-80 percent in southern California cotton has been reported under full-season production (Gerling 1967, Natwick and Zalom 1984, Bellows and Arakawa 1988), but seldom reaches 40 percent under short-season production (Hoelmer 1996). Early-season parasitism in southern California has not sufficiently controlled sweetpotato whitefly population growth,

but *Eretmocer* parasitism always exceeded that of *Encarsia* (Coudriet et al. 1986). Similarly in Israel, populations of *Encarsia lutea* (Masi) and *Eretmocer mundus* (Mercet) peak in early and mid September, respectively, following sweetpotato whitefly peak populations and have not afforded an acceptable degree of population suppression (Gerling et al. 1980). In the Sudan, Gameel (1969) found that the highest parasitism of sweetpotato whiteflies was reported to be caused by *E. lutea* (66 percent) followed by *E. mundus* (34 percent). In Egypt, parasitism by *E. mundus* averaged 44.4 to 73.0 percent in insecticide-treated cotton and 34.0 to 55.4 percent in insecticide-treated cabbage and from 78.6 to 80.8 percent in untreated *Lantana camara* L. (Hafez et al. 1979). Similar results in Egypt were reported on cotton, soya, cauliflower, and tomato (Abdel-Fattah et al. 1986) and a number of other vegetable crops (Abdel-Gawaad et al. 1990). Although various studies have reported high levels of nymph parasitism, these results have never been definitively associated with economic suppression of populations.

The effect of predator populations on sweetpotato whitefly population dynamics is even more difficult to characterize because of methodological problems (Naranjo and Hagler 1998, Naranjo et al. 1998b). Immunological analyses of predator gut contents in Arizona cotton revealed frequencies of predation ranging from 4-38 percent for nine heteropteran and beetle predators (Hagler and Naranjo 1994a,b). Life tables studies within the same area demonstrate that predation by piercing-sucking predators alone accounts for over 35 percent of all immature sweetpotato whitefly mortality on cotton. Although the overall effects of predation are not completely understood, evidence suggests that it may play a critical role in long-term pest suppression with the use of selective insecticides (Ellsworth and Martinez-Carrillo 2001, Naranjo 2001).

## Management Strategies

Considerable progress has been made in development, demonstration, and implementation of an integrated pest management strategy for sweetpotato whiteflies on cotton. Conceptually, this management system can be viewed as a pyramid (Ellsworth and Martinez-Carrillo 2001, Naranjo 2001) consisting of 3 key elements (figure 2):

- (1) a foundation of “avoidance” tactics and strategies that serve to reduce pest population levels,



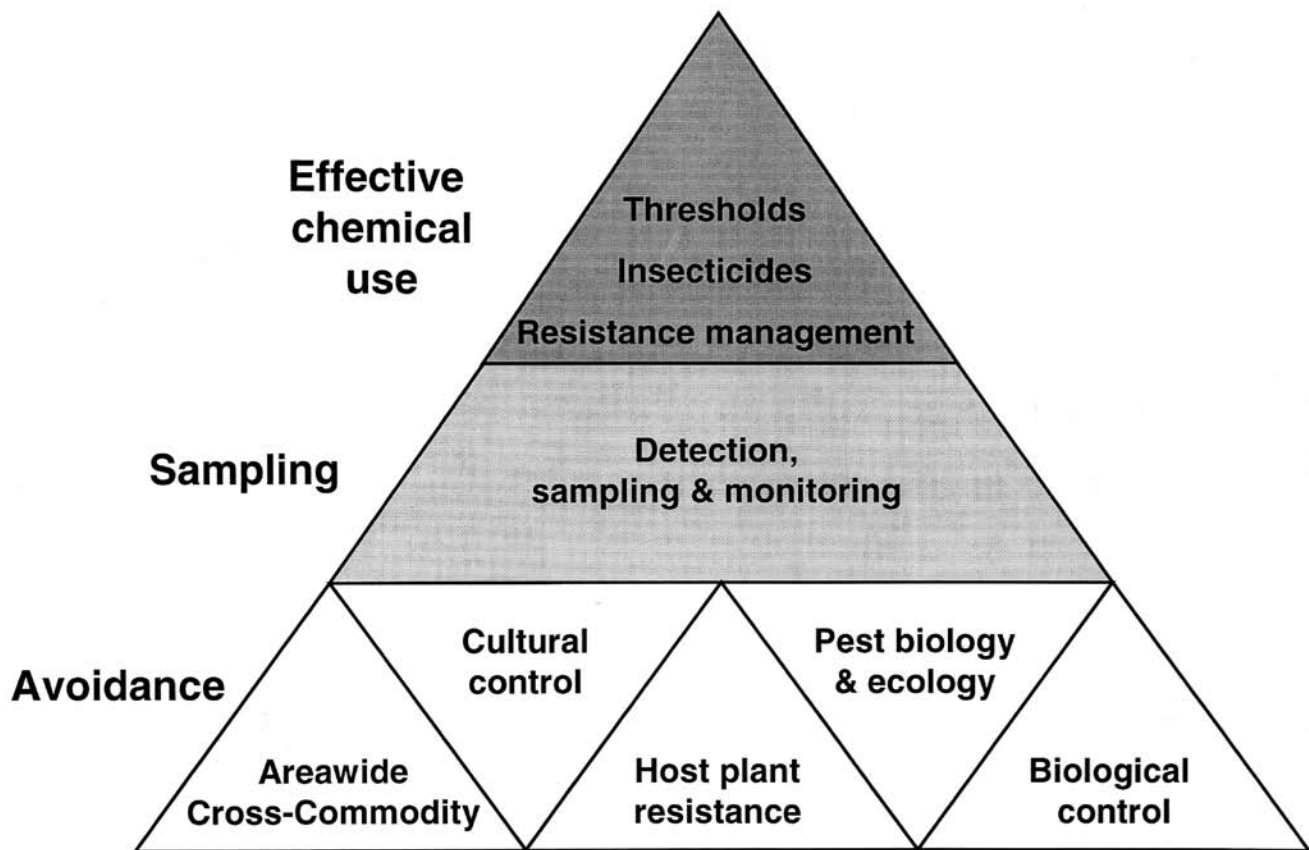


Figure 2. Conceptual diagram of integrated whitefly management in cotton. The pyramid structure is inherently stable and contains three keys to whitefly management: avoidance, sampling, and effective chemical use (From Ellsworth 1999, Naranjo 2001).

- (2) sampling methods for detection and monitoring of pest population and associated problems, and
- (3) effective use of insecticides based on action thresholds and resistance management considerations.

During the past decade, this current paradigm has evolved from a crisis-driven, two-dimensional system of broad-spectrum chemical management to a multifaceted three-dimensional and integrated management strategy (Ellsworth et al. 1996a,b,c, 1999, Ellsworth and Naranjo 1999). Although the two upper levels of the pyramid are the best developed and are the basis of short-term management approaches, sustainable, long-term strategies depend development and inclusion of the broad-based foundation of pest avoidance.

### Sampling

Well-designed sampling tools are essential for progress in all areas of whitefly research and management, and several comprehensive reviews of sampling have been published (Butler et al. 1986, Ohnesorge and Rapp 1986, Ekbohm and Rumei 1990, Naranjo 1996). Sampling of eggs and nymphs requires the collection and examination of individual leaves, in situ, with the aid of a microscope or hand lens. The distribution of the insects within the field, as well as on the plant, is variable and may affect the results. Spatial distributions of sweetpotato whitefly eggs and nymphs on two upland cotton cultivars and on one Pima cotton cultivar were reported by Naranjo and Flint (1994). The greatest numbers of eggs and nymphs were found on main stem cotton leaves from nodes 2 to 4 and 4 to 7, respectively, while the lowest coefficients of variation were associated with leaf counts from nodes 4 to 5 for eggs and 5 to 6 for nymphs. Variance partitioning and sampling cost analysis showed that a single 3.88 cm<sup>2</sup>

leaf disk (approximately the size of a U.S. quarter) from the proximal underside surface enclosed by the main leaf vein and the left primary plant vein from the 5th mainstem node was the most efficient sampling unit for estimating egg and nymph densities. Naranjo and Flint (1994) present density-dependent sample size curves and fixed-precision sampling plans based on this sample unit.

A wider range of methods are available for sampling adults (Butler et al. 1986); however, Naranjo et al. (1995) compared a number of methods and demonstrated through a quantitative cost analysis that in situ counts of adults on the underside of cotton leaves was the most efficient. Naranjo and Flint (1995) found that adult sweetpotato whiteflies are consistently more abundant on mainstem leaves at the tops of cotton plants than on leaves from the middle and bottom of cotton plants. The adults were fairly uniformly distributed over leaves on mainstem nodes 2-7 from the terminal, but counts from the 5th node were least variable. As with immatures, Naranjo and Flint (1995) described density-dependent sample sizes and developed fixed-precision sequential sampling plans for adults. Using a resampling methodology to validate sample plan performance, the authors reported that for action thresholds of 5 to 10 adults per leaf their results suggested that fewer than 20 leaf samples were required to estimate adult densities with a precision (standard-error to mean ratio) of 0.25. A binomial sampling plan for adults was subsequently developed to estimate population density from the proportion of leaves infested with a predetermined number of insects (tally count) (Naranjo et al. 1996a,b). For cotton it was found that a tally count of three was optimal in terms of the sample size needed to make a correct control decision relative to an action threshold. On average, fewer than 30 samples were required (Naranjo et al. 1996a). These binomial sampling plans form the foundation of the decision-making protocol discussed below.

### **Effective Chemical Use**

Action thresholds, selective and effective types of chemicals, and resistance management are the foundation of effective chemical control. The integration of these factors with the sampling information presented above form the current management system employed in the southwestern U.S. cotton production area.

### **Action Thresholds**

That insecticides should be used only when absolutely necessary has been a basic principle in pest management over the past 40 years. A variety of approaches have been used over the past decade to develop action thresholds for the judicious use of insecticides in the management of sweetpotato whiteflies in cotton (Ellsworth and Meade 1994, Naranjo et al. 1996a, 1998a). Early work in Arizona (Ellsworth and Meade 1994) and other parts of the world (Mabbett et al. 1980, Sukhija et al. 1986, Stam et al. 1994) helped define boundaries that facilitated further, more detailed analyses. Naranjo et al. (1996a) estimated economic injury levels by examining the relationship between pest density and damage, using a range of values for crop price, insecticide efficacy, and control costs. A multistate, multi-institution study estimated action thresholds based on controlling whiteflies with conventional chemicals when adult densities exceeded various predetermined levels (Naranjo et al. 1998a). Results of this study demonstrated that there was little difference in whitefly population density or cotton yield response when insecticide treatments were initiated at action thresholds of 2.5 to 10 adults per leaf, but that net economic return was generally highest for action thresholds of 5 to 10 adults per leaf. A threshold of 5 adults per leaf has been adopted in Arizona and the Imperial Valley of California (Ellsworth et al. 1994) while 10 adults per leaf is recommended in the San Joaquin Valley with the use of conventional insecticides. These action thresholds were later modified, tested, and optimized for proper deployment of insect growth regulators that became available in 1996 (Ellsworth et al. 1996c, 1997, 1998).

### **Selective Insecticides**

Experiences in other parts of the world (see Horowitz and Ishaaya 1996) helped refine the list of candidate compounds for control of sweetpotato whiteflies, and initial coordinated efforts using standardized protocols (Faust 1992) further identified the most promising compounds or mixtures in the United States. These provided only temporary relief, and diminishing susceptibility to pyrethroid combinations in 1995 precipitated the unprecedented Section 18 emergency exemption to Arizona in 1996 for two new insect growth regulators (IGRs) (Dennehy et al. 1996, Ellsworth et al. 1997). These IGRs, pyriproxyfen and buprofezin, have been effective for sweetpotato whitefly management in cotton (Ellsworth et al. 1997, Ellsworth and Naranjo 1998) and nondisruptive to

natural enemy populations in the system (Naranjo 2001). This combination of qualities contributes to the foundation of the IPM pyramid (figure 2). Detailed partial life table studies of sweetpotato whiteflies in cotton have clearly identified and quantified the respective roles of types of insecticides and natural enemy conservation as integral components of the management system for sweetpotato whitefly (Ellsworth and Martinez-Carrillo 2001, Naranjo 2001). Additionally, the use of imidacloprid in melons and vegetables has strengthened management effectiveness over the entire agricultural community (Palumbo et al. 2001). The major effect of imidacloprid treatment of melons and vegetables has been that of breaking the host linkage from melons to cotton in the spring and cotton to vegetables in the fall.

### **Insecticide Resistance Management**

The ability of sweetpotato whiteflies to develop resistance to a wide range of chemical insecticide classes has been well known for many years. To explicitly address this problem, insecticides have been organized into a three-stage program of deployment for resistance management (Ellsworth and Martinez-Carrillo 2001). The first stage of this strategy suggests application of IGRs based on a developed action threshold of 0.5 to 1.0 large nymph per leaf disk and 3 to 5 adults per leaf turn (Ellsworth et al. 1996c, 1997) and is based on the tested premise that the materials are most effective when timed to coincide with the initial reproduction of immigrant adult whiteflies. Both IGRs are restricted to a single application per season to reduce resistance development. Buprofezin is a chitin-synthesis inhibitor effective against nymphal instars. Pyriproxyfen is a juvenile hormone that sterilizes adults and eggs and interferes with adult emergence from the final nymphal stages.

Delaying the deployment of stage II (nonpyrethroid) and stage III (pyrethroid mixture) insecticides, limiting mixtures to two chemicals, and limiting the use of any active ingredient to two times in the season are additional methods to delay resistance development. Stage II insecticides are triggered at an action threshold of an average of five adults per leaf using leaf-turn sampling procedures previously described. Materials include cyclodiene, nicotiny, carbamate diamidide, and organophosphate insecticides. Application of some of these chemicals may be effective when applied alone. Many of the stage II chemicals are used in combinations. It is suggested that no more than two insecticides be used in mixtures. Stage III

insecticides are pyrethroid insecticides used under carefully monitored control. No more than two applications per season and rotation of the pyrethroids are recommended. In stage II, chemical mixtures also should not use more than two chemistries. Stage III chemical use, because of resistance potential, should be delayed as late in the season as possible. Significant progress in cross-commodity use patterns and more explicit recognition of spatial and temporal consideration in sequential crop establishment and proximity of alternate hosts (source reduction) have significantly reduced intercrop movement (see Palumbo et al. 2001).

### **Decision Protocols**

The integration of “Sampling” and “Effective chemical use” (figure 2) has resulted in a research-rich, but simple, set of guidelines for the efficient and effective sweetpotato whitefly management in cotton (figure 3). The protocol uses simultaneous binomial sampling of adult and large nymphs and a decision matrix to time applications of IGRs during stage I management. Briefly, the underside of the 5th mainstem leaf (from the terminal) is inspected for the presence of three or more adult whiteflies. This leaf is then detached and examined (naked eye or weak magnification) for the presence of at least one large nymph within an area roughly the size of a quarter at the proximal end of the leaf between the central and left major veins. A complete sample consists of 30 leaves observed from quasi-random transects in at least two quadrants (15 per quadrant) of a 16-32 ha field. The percentage of leaves infested with adults and large nymphs is then calculated and converted to density per leaf or disk using the binomial conversion tables. These density values are then applied to determine which of the four choices in the IGR decision matrix to use. The entire process takes roughly 7 minutes to complete and is extremely accurate in determining the need for control (Naranjo et al. 1997). Adult sampling alone is used to make treatment decisions using stage II and III materials.

### **Discussion**

Areawide programs with high grower participation in standardized crop production methodology and chemical control use patterns are generally more effective than individual growers using widely diverse and often conflicting methods. Chemical control is only one component of an integrated management program for sweetpotato whitefly control on cotton. Management begins at planting with selection of

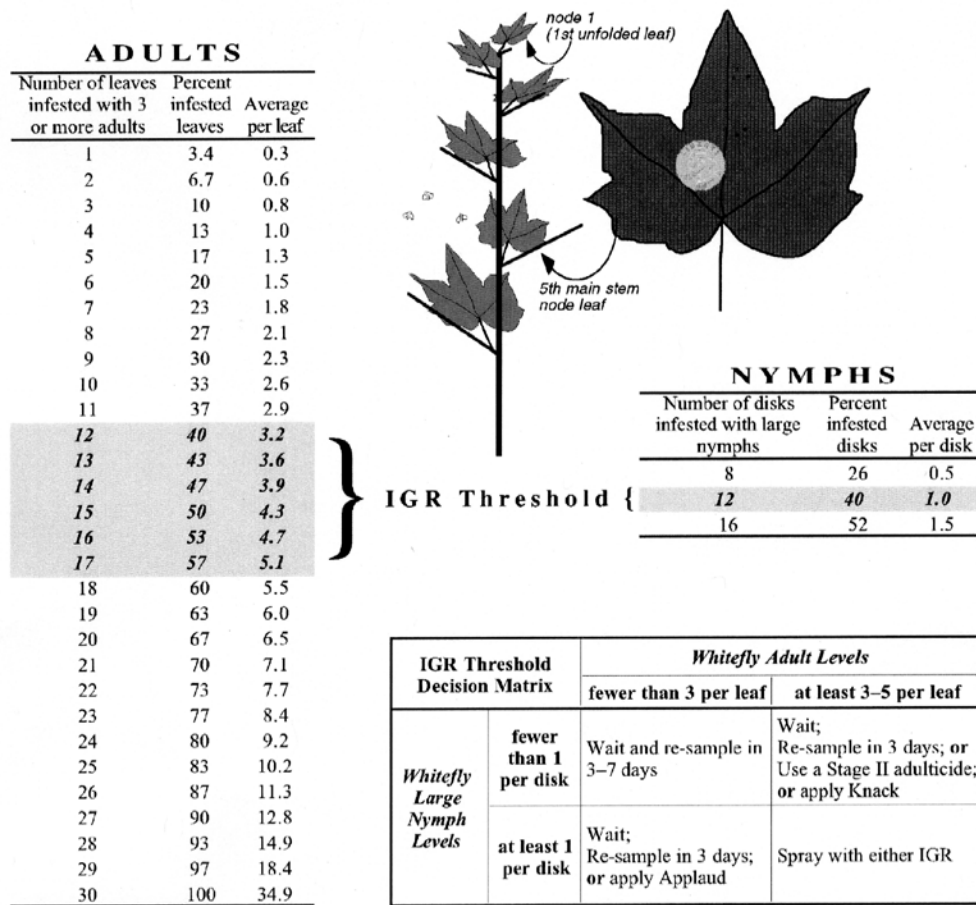


Figure 3. Decision protocol for management of *B. tabaci* on cotton, including description of sample units, binomial conversion tables for adults and large nymphs (3rd or 4th instars), and decision matrix for IGR. Protocol is based on a 30-leaf sample (adapted from Ellsworth et al. 1996a,b,c, Naranjo and Flint 1994, Naranjo et al. 1996a,b; reproduced with permission from Elsevier Science Ltd).

smooth-leaf varieties that support lower populations than hairy cottons. Earliness and uniformity of planting with early termination goals are encouraged. During the season, water management and efficient fertilizations are essential to avoid plant stress. Early harvest and destruction of crop residues prevents development of additional generations of whiteflies that can disperse to other crops. Allowing host-free periods between susceptible crops that are as long as possible is a highly effective management approach.

The integration of chemical control with resistance management, crop sequencing and host-free periods,

crop residue and weed destruction, sweetpotato whitefly population and plant disease monitoring, and other cultural controls and management options is considered a high priority for future research. Additional tools such as descriptive models and geographical information systems are envisioned as components of large areawide programs. In most areas with sweetpotato whitefly problems, steps are being taken to organize these approaches into coordinated community-action programs. Such programs have proven effective where they have been developed (Ellsworth et al. 1997, 1999, Ellsworth and Naranjo 1999). Crop plants resistant to sweetpotato whiteflies

and disease, natural-product and microbial insecticides, and natural enemy introduction and augmentation also have potential as integrated-management components for sweetpotato whitefly control.

Currently, effective sweetpotato whitefly management has been accomplished with (1) selection of cultivars that are not preferred by sweetpotato whiteflies; (2) selected spatial and temporal modification of sequential crop systems; (3) intensive sampling and monitoring of whitefly populations; (4) chemical control focused on natural enemy conservation, established action thresholds, alternating chemical modes of action, and resistance monitoring; (5) optimum crop yield

goals, allowing for early harvests and destruction of crop residues; and (6) active education and extension outreach to provide timely communication of new developments, sweetpotato whitefly population dynamics, and other pertinent information to growers. Not all of the management components are applicable to or used in all areas or for all crops, but are general principles that provide the agricultural community options for consideration in sweetpotato whitefly management. Additionally, the systems remain open-ended and receptive to other compatible sweetpotato whitefly management components (Henneberry and Nichols 2002).

**Table 1. Selected publications on effects of temperature on *Bemisia tabaci* (fecundity and egg hatch) on cotton**

Temperature <sup>a</sup>	Eggs per female	Hatch	Source
°C		%	
9.4-42	28-43	–	Husain and Trehan 1933
15-40	160	59-98	Gameel 1978
25-26	257	–	Gameel 1978
26.7	81	68	Butler et al. 1983
32.6	72	75	Butler et al. 1983
30.0	95	–	Horowitz 1983
22-30	93	–	Horowitz 1983
27.0	128	–	Von Arx et al. 1983
25-26*	309-344	–	Dittrich et al. 1985
25-26.5	257-286	–	Dittrich et al. 1985
26.7	31.8	–	Dittrich et al. 1985
20.0	–	84.5	Powell and Bellows 1992
25.5	–	90.5	Powell and Bellows 1992
29.0	–	98.0	Powell and Bellows 1992
32.0	–	94.9	Powell and Bellows 1992
26.7	51.2	–	Bethke et al. 1991

Source: Henneberry and Castle 2001

<sup>a</sup> Experimental environment:

asterisk = field or greenhouse conditions

no asterisk = controlled temperature and lighting conditions.

**Table 2. Selected publications on effects of temperature on *Bemisia tabaci* egg and nymph development on cotton<sup>1</sup>**

Temperature	Egg development	Nymph development					Total egg to adult	Source
		Instar 1	Instar 2	Instar 3	Instar 4	Instar 4		
°C		days.....						
9.4 to 42.0*	3-33	-	-	-	-	2-8	14-107	Husain & Trehan 1933
14.9	-	-	-	-	-	-	65.1	Butler et al. 1983
16.7	22.5	-	-	-	-	-	48.7	Butler et al. 1983
20.0	11.5	-	-	-	-	-	34.7	Butler et al. 1983
22.5	9.9	-	-	-	-	-	27.8	Butler et al. 1983
25.0	7.6	-	-	-	-	-	23.6	Butler et al. 1983
27.5	6.1	-	-	-	-	-	17.8	Butler et al. 1983
30.0	5.4	-	-	-	-	-	16.6	Butler et al. 1983
32.5 **	5.0	-	-	-	-	-	-	Butler et al. 1983
30.0	5.3	2.5	3.0	2.6	4.3	17.7	Horowitz 1983	
15.0	20.5	-	-	-	-	-	-	Gameel 1978
20.0	11.8	-	-	-	-	-	-	Gameel 1978
25.0	8.3	-	-	-	-	-	-	Gameel 1978
30.0	7.5	-	-	-	-	-	-	Gameel 1978
35.0	5.8	-	-	-	-	-	-	Gameel 1978
40.0	5.2	-	-	-	-	-	-	Gameel 1978
26.7	-	2.9	2.1	3.0	5.3	23.3	Bethke et al. 1991	
20.0	8.8	4.9	3.3	3.4	8.3	28.6	Powell & Bellows 1992	
20.0	4.8	3.4	1.7	2.4	5.3	17.7	Powell & Bellows 1992	
29.0	4.2	5.2	2.3	2.3	5.2	19.1	Powell & Bellows 1992	
32.0	3.9	4.6	2.1	2.2	5.4	18.3	Powell & Bellows 1992	
26.7	-	4.1	2.3	3.2	6.6	23.6	Bethke et al. 1991	
21.3(J)**	10-12	3.4	7-8	6-8	7-8	37.0	Gameel 1978	
23.1(F)	10-11	3.4	6-8	7-8	7-8	36.0	Gameel 1978	
26.8 (M)	8-10	3.4	7-8	7-8	7-8	35.0	Gameel 1978	
31.0 (A)	7-9	3.4	5-7	6-7	6-7	31.0	Gameel 1978	
33.3 (M)	7-8	2.4	5-7	5-6	5-7	29.0	Gameel 1978	

Table 2 cont'd. Selected publications on effects of temperature on *Bemisia tabaci* egg and nymph development on cotton<sup>1</sup>

Temperature	Egg development	Nymph development					Total egg to adult	Source
		Instar 1	Instar 2	Instar 3	Instar 4	Instar 4		
°C				days.....				
33.5 (J)	6-8	2.3	4-6	4-6	4-6	5-7	27.0	Gameel 1978
28.2 (J)	6-7	3.0	4-6	4-6	4-6	4-6	28.0	Gameel 1978
26.0(A)	6-7	3.0	4-5	4-5	4-5	4-6	28.0	Gameel 1978
28.0 (S)	6-8	2.3	5	4-5	4-5	4-6	29.0	Gameel 1978
28.2 (O)	6.0	2.4	5	4-6	4-6	4-7	28.0	Gameel 1978
26.6 (N)	6-8	3.4	6	4.6	4.6	5-7	32.0	Gameel 1978
22.3 (D)	8-10	3.4	5.7	5.6	5.6	6.8	35.0	Gameel 1978

Source: Henneberry and Castle (2001)

<sup>1</sup> Experimental environment:

one asterisk = field or greenhouse conditions

two asterisks = unspecified laboratory conditions

three asterisks = monthly data in the field

no asterisk = controlled temperature and lighting

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## Chapter 7

### Biology and Management of the Cotton Aphid

*J.E. Slosser and L.D. Godfrey*

Significant lint contamination by cotton aphid honeydew occurred in California in 1986 (Perkins and Bassett 1988) and in 2001 and in the Texas High Plains in 1995 (Lloyd 1997). The 1995 Texas problem was a combination of cotton aphid honeydew and plant physiological sugars resulting from an early frost. The 2001 problem in California was a combination of cotton aphids and sweetpotato whiteflies. Sticky lint problems in Arizona in 1992 were caused primarily by sweetpotato whiteflies, but cotton aphids were partially responsible for some of the lint contamination. Thick honeydew coatings on cotton leaves prevented effective harvest-aid termination of some fields in the High Plains and Rolling Plains in Texas in 1999, but subsequent rainfall cleansed the leaves and lint.

Cotton aphids became a serious problem on cotton in the Texas Rolling Plains and High Plains in 1975 (Rummel et al. 1995, Slosser et al. 1997a). After this initial heavy infestation, problems moderated until the early 1980s, but infestation levels have been high every year since the mid 1980s throughout West Texas (Leser et al. 1992). In California, the importance of this pest to cotton production has changed significantly in the last 15 years. Before the mid 1980s, the cotton aphid was considered, at worst, an occasional pest in the California San Joaquin Valley. Beginning in about 1986, significant infestations of cotton aphids were seen on seedling cotton and on late-season cotton. Infestations as high as 25.6 aphids per square centimeter were commonly seen on seedling cotton (Rosenheim et al. 1997). Infestations on midseason cotton (June to August) were minimal until 1992, when populations became significant and damaging. Severity of midseason cotton aphid infestations peaked in 1995 and 1997. Reasons for this shift in cotton aphid population timing and severity are unclear; however, the yield losses and threat of contaminated lint from cotton aphids means that aphid control has become

a necessary production cost for California cotton growers.

In Texas the potential for sticky lint problems extends throughout the southern and northern Rolling Plains and High Plains regions, although the Rolling Plains has not experienced a sticky lint problem because rain during September and October, when bolls are opening, cleanses the lint of any honeydew contamination. Cotton production in southwestern Oklahoma is similar to that in the northern Texas Rolling Plains; and while a potential for sticky lint at harvest exists, problems have been few if any. Sticky lint caused by cotton aphids has not been a reported problem in New Mexico, although there have been indications of sticky lint south of Las Cruces. In Arizona a perennial risk exists in the higher elevations of cotton production including Graham, Greenlee, and Cochise Counties in the southeastern part of the state. However, with the exception of 1992, there has been little aphid-related sticky lint problems. In California, the entire San Joaquin Valley has the potential for high aphid levels and for sticky lint, but the desert production region is not conducive to aphid buildup.

#### Seasonal Distribution

The large numbers of cotton aphids infesting seedling cotton led producers to question where the aphids were overwintering and from what site populations were originating. Cotton aphids have been reported to feed on over 300 plant species. The life cycle (figure 1) has been studied in detail in California. Cotton aphids overwinter as both viviparous individuals and as eggs, and melons and other crops are common spring hosts (Cisneros et al. 2001). Low numbers of aphid nymphs and adults were found on annual winter weeds such as whitestem filaree, prickly lettuce, shepherd's purse, chickweed, and london rocket, and some individuals were also observed on the new growth of citrus trees throughout the winter. In addition, large numbers of cotton aphid eggs were found on pomegranate twigs and leaf buds beginning in December; sexual form aphids were found from October to December. The pomegranate orchards surveyed during this study harbored substantial numbers of fundatrices (first generation of asexual aphids that develop from eggs) in late winter (February), which built up to large aphid populations with numerous alates (April). These alates are believed to play an important role in colonizing other spring-summer crops, making the pomegranate host a potentially important source of aphids in the San

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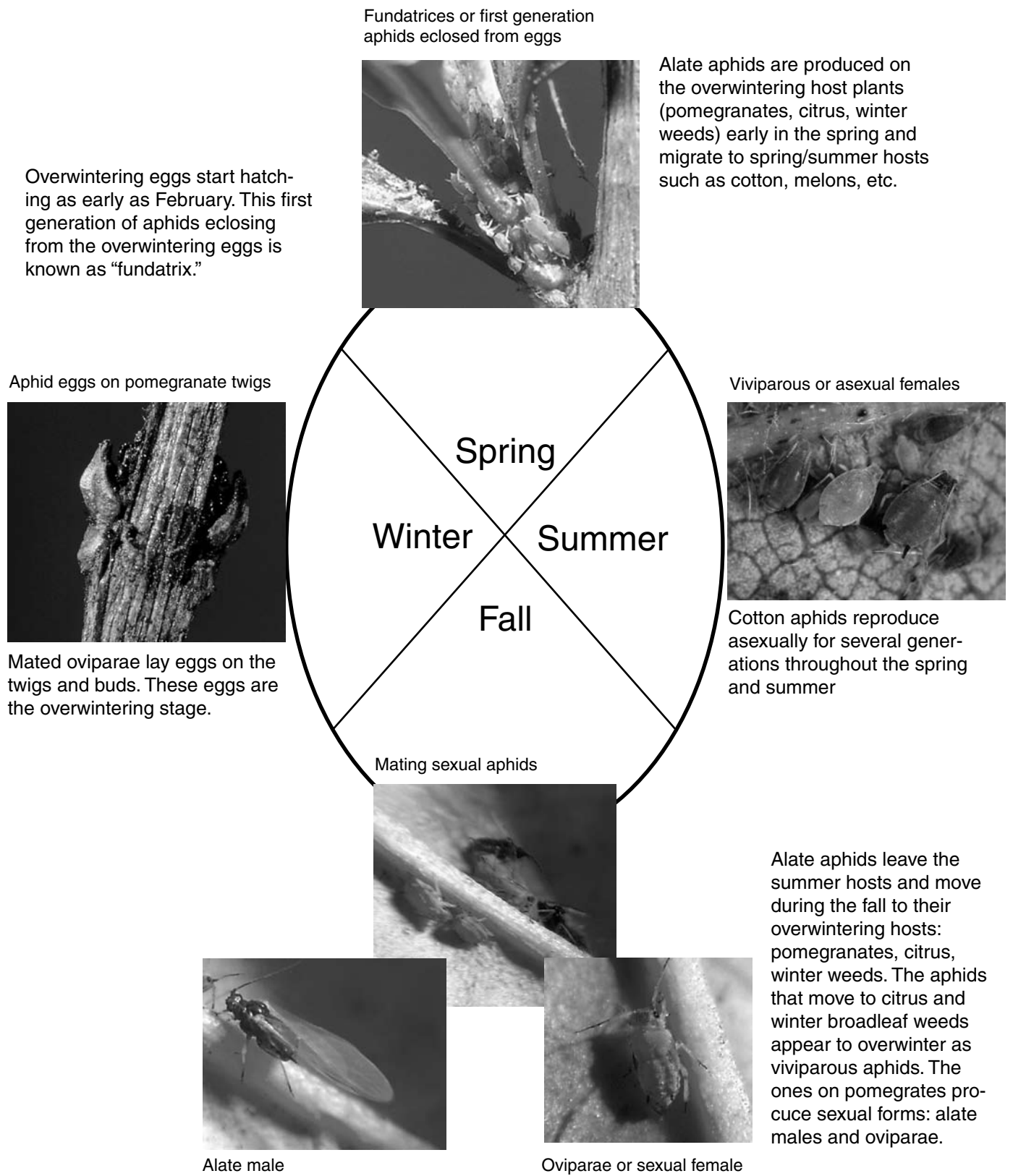


Figure 1. Cotton aphid life cycle in California.



Joaquin Valley. O'Brien et al. (1993) characterized the cotton aphid seasonal biology and seasonal host plants in the Mid-South system and reported 24 different noncultivated host plants representing 18 plant families.

In Texas, males have been collected in an insect suction trap during November and early December from 1992 to 1994, and males were found on cotton plants within predator exclusion cages in November 1994. However, no gravid females have been found on cotton or in suction traps on the High Plains near Lubbock, TX (Parajulee et al. 2003). O'Brien et al. (1990) reported cotton aphid sexual morphs from a collection on November 20, 1988, from cotton plants in west-central Mississippi.

### **Population Dynamics—Summer Trends**

#### **Texas**

When cotton is planted by early May, cotton aphids may colonize and stunt the growth of a few individual plants throughout the field by early June. These early infestations do not persist, and by late June it is difficult to detect aphid infestations. Cotton aphid numbers generally remain below 10 per leaf throughout June and July. Aphid populations begin to develop rapidly after early August, and peak numbers can exceed 600 per leaf between mid August and mid September. High population levels are not sustained, and aphid populations typically decline to levels below 5 per leaf within 2-3 weeks after the population peak (Slosser et al. 1992b, 1998).

Under some conditions, cotton aphid populations have increased to high levels requiring insecticidal control during July. The conditions that contribute to such early aphid population development include frequent irrigations at 3-4 day intervals, usually with a center-pivot system, and application of high levels of nitrogen fertilizer. These cultural conditions induce development of tall plants during July that modify the environment within the plant canopy, enhancing aphid reproduction. Development of high population levels during July is the exception, with the general rule being development of high population levels after mid August.

Cotton planting date exerts a strong influence on population levels during August and September. In a study at Chillicothe, TX, peak population density was highest in cotton planted in late June in six of seven years compared to peak population numbers in

cotton planted in late April and late May (figure 2). However, aphid numbers in April-planted cotton may exceed numbers in June-planted cotton if the April-planted cotton has begun a new cycle of regrowth by late August. Plant nutrition (leaf moisture and leaf nitrogen) is an important variable that influences aphid population density during August and early September, and June-planted cotton typically has high levels of leaf moisture and nitrogen, which favor aphid population development. Population trends such as timing of population increase and the date of peak population numbers are not influenced greatly by planting date (Slosser et al. 1998).

Generally there is only one population peak during the growing season. If the aphid population peaks by mid August, a second population peak can occur during September. Population peaks after mid August have not been followed by a second peak during the fall. In years with sustained high temperatures and drought conditions during July and August, population does not build up until September, and in these cases, populations may peak between mid September and mid October. High population levels during August can reduce yields, while population peaks during September and October potentially contribute to a sticky lint problem.

#### **California**

Since the early 1990s, cotton aphid infestations on presquaring cotton have been uncommon. The predominance of use of an at-plant systemic insecticide in areas that are prone to early-season aphid infestations is the primary reason for this shift. Infestations commonly run from peak bloom to defoliation (July and August). Population peaks (figure 3) are generally higher on later planted cotton (May) compared with planted fields earlier (late March to April); this is likely caused by higher nitrogen availability. In unsprayed plots, the aphid population increases gradually over a 2-3 week period, reaches a distinct peak, then declines rapidly (see figure 5 in Cisneros and Godfrey 2001a and figure 5 in Cisneros and Godfrey 2001b for examples). A low level of aphids may persist following this decline, but a drastic increase in levels is not generally seen again during the season. This low level of aphids can, however, still be threatening to cotton lint quality. The decline in population density is likely the result of the actions of generalist predators; however, unfavorable environmental and host plant conditions undoubtedly also contribute to this decline.

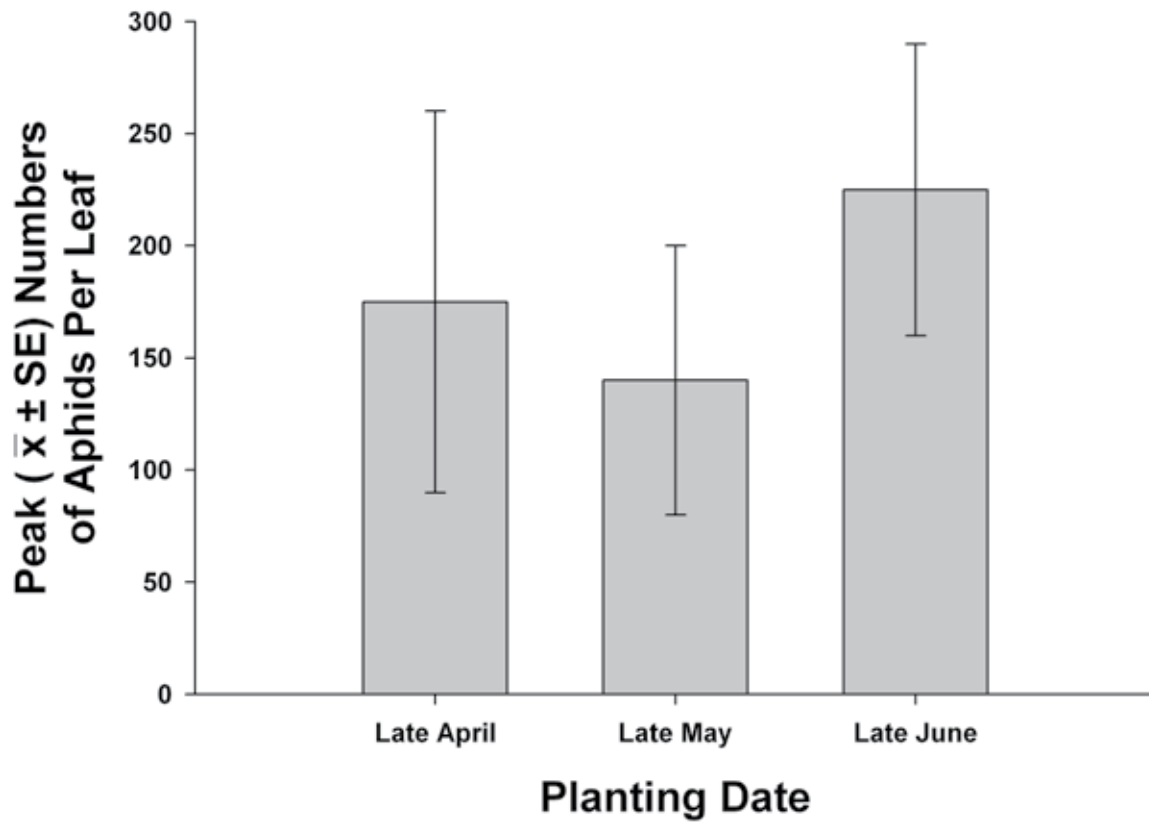


Figure 2. Influence of planting date on peak numbers ( $\bar{x} \pm SE$ ) of aphids per leaf during August and early September. Chillicothe, TX, 1988-1994.

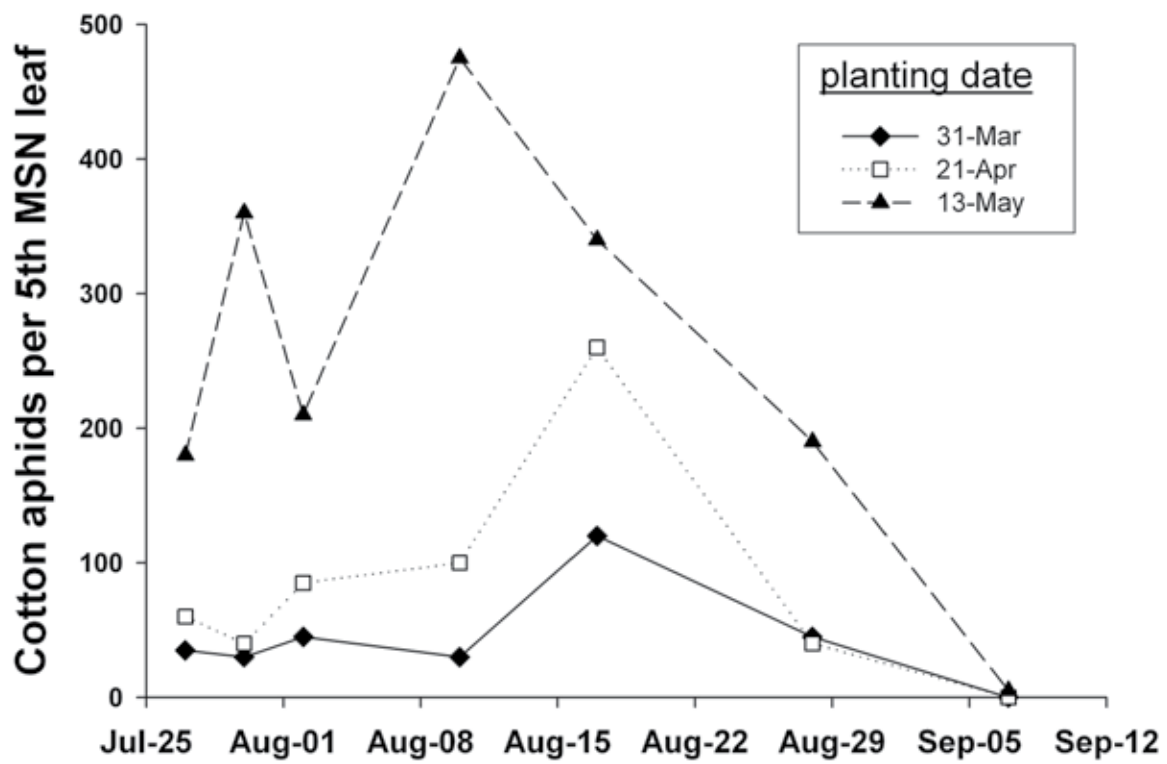


Figure 3. Influence of cotton planting date on cotton aphid population dynamics. Shafter, California, 1994.

## Treatment Thresholds

### In-Season Thresholds

Fuchs and Minzenmayer (1995) demonstrated that lint and seed yields were significantly reduced when aphid numbers exceeded 50 per leaf for three weeks during August and early September. Yield reductions ranged from 103 to 150 lb/acre of lint (115-168 kg/ha). One factor responsible for the lower yields was reduced boll weights. Price et al. (1983) also documented yield reductions of about 100 lb/acre (112 kg/ha) where aphid numbers approached 100 per leaf by mid August. In Texas, the recommendation is to delay control of cotton aphids until infestations exceed 50 per leaf from early bloom to first open boll (Slosser et al. 2003).

Cotton aphid infestations on presquaring cotton have been shown to have no effect on cotton lint yield (Rosenheim et al. 1997). Although aphid numbers can be very high, the infestations are generally of short duration because natural enemies quickly bring infestations in check. If conditions are such that infestations are favored and therefore persist, these early-season infestations may be problematic, but this is rare. Midseason aphid infestations can reduce boll size and high densities of aphids can cause boll shed. During midseason (squaring to first boll opening), a treatment threshold of 50 to 100 aphids per leaf with infestations persisting for 7 to 10 days is recommended in California (Fuson et al. 1995, Godfrey et al. 1997, Godfrey and Wood 1998).

### Late-Season Thresholds

When bolls begin to open and lint is potentially exposed to aphid honeydew, treatment thresholds are lower than during the growing season. Slosser et al. (2002) have shown that 11-50 aphids per leaf can cause a sticky lint problem in Texas. The threshold for aphids was lower (11 per leaf) when leaf nitrogen and leaf moisture were lower (2.5 percent and 63 percent, respectively), while the threshold was highest (50 per leaf) when leaf nitrogen and moisture were higher (2.9 percent and 69 percent, respectively). Apparently, plant stress, as indicated by lower percentages of leaf nitrogen and moisture, results in the deposition of unacceptable levels of melezitose on lint by cotton aphids. Following boll opening, a treatment threshold of 10-15 aphids per leaf is used in California to minimize the deposition of honeydew on the exposed lint (Rosenheim et al. 1995, Godfrey et al. 2000a).

## Population Sampling

Several sampling protocols have been used in Texas to determine number of aphids per leaf. Fuchs and Minzenmayer (1995) sampled upper canopy (fourth fully expanded leaf below the terminal) and midcanopy leaves. Slosser et al. (1998) sampled leaves from the top half and from the bottom half of the plant, and Slosser et al. (1992a) reported that aphid numbers were higher on leaves from the bottom half of the plant on cotton that was planted in June. In another study, Slosser et al. (1997a) reported that aphid numbers were higher in top-half leaves in June-planted cotton and lower in top-half leaves in April-planted cotton. Thus, year and planting date influence aphid abundance and distribution on the plant, and selection of leaves from one location on the plant may not provide valid estimates of aphid numbers. In Texas, management guidelines suggest sampling 20 leaves from each of the top, middle, and lower portion of plants across the field to determine infestation levels.

In California, cotton aphid sampling is concentrated on the fifth main stem node leaf from the plant terminal. This leaf generally has one of the highest aphid population levels and it is also the recommended leaf for monitoring sweetpotato whiteflies and spider mites (*Tetranychus* spp.). Presently, quantification and estimation of the infestation density is visual. All life stages (adults and nymphs) and all morphs (dark, light, and alate) should be counted.

## Biotic and Abiotic Environmental Influences

Slosser et al. (1998) monitored aphid populations in cotton planted in late April, late May, and late June for 7 consecutive years. Plant phenology (initiation of blooming, for example) was not associated with aphid population buildup because aphid numbers increased at the same time during August after all three planting dates. There was a significant interaction between the abiotic and biotic environments that regulated aphid populations during August. High temperatures (particularly under the leaf), solar radiation (which includes components for temperature and light intensity), and plant nutrition (leaf nitrogen and leaf moisture) were the environmental components that interacted to regulate aphid numbers per leaf after all three planting dates. High temperatures affected aphid numbers most in cotton that was maturing (low square-to-boll ratio, particularly on cotton planted in late April) during August. Plant nutritional effects

(leaf nitrogen and leaf moisture) were the primary factors regulating aphid numbers during August in cotton that was immature (high square-to-boll ratio, particularly late June planting). Temperature was the most important variable, but temperature effects were moderated by plant nutritional status.

A range of color morphs, from pale yellow to nearly black of cotton aphids (figure 4) are commonly seen in California. Rosenheim et al. (1995) reported on life table parameters from these various morphs and found that the dark-colored individuals developed more rapidly from birth to adult, produced their offspring earlier during the adult stage, and produced more offspring than the lighter individuals. Favorable environmental conditions, lower temperatures, high fertility hosts, and shorter day-lengths resulted in

the production of the dark aphid morph in laboratory studies. Factors regulating the morph production under field conditions have not been fully evaluated, but Nevo and Coll (2001) reported that aphids feeding on nitrogen-fertilized plants were bigger and darker than those feeding on plants with no nitrogen fertilizer.

Aphid numbers during August were not influenced by predator numbers for any planting date in the 7-year study (Slosser et al. 1998). However, the rate of aphid population decline after peak abundance in August was strongly influenced by predator abundance for all three planting dates, but plant nutrition also influenced the rate of aphid population decline. When plant nutrition was favorable, predators were less effective, apparently because aphid reproduction offset losses caused by predators. Parajulee et al. (1997) demonstrated that

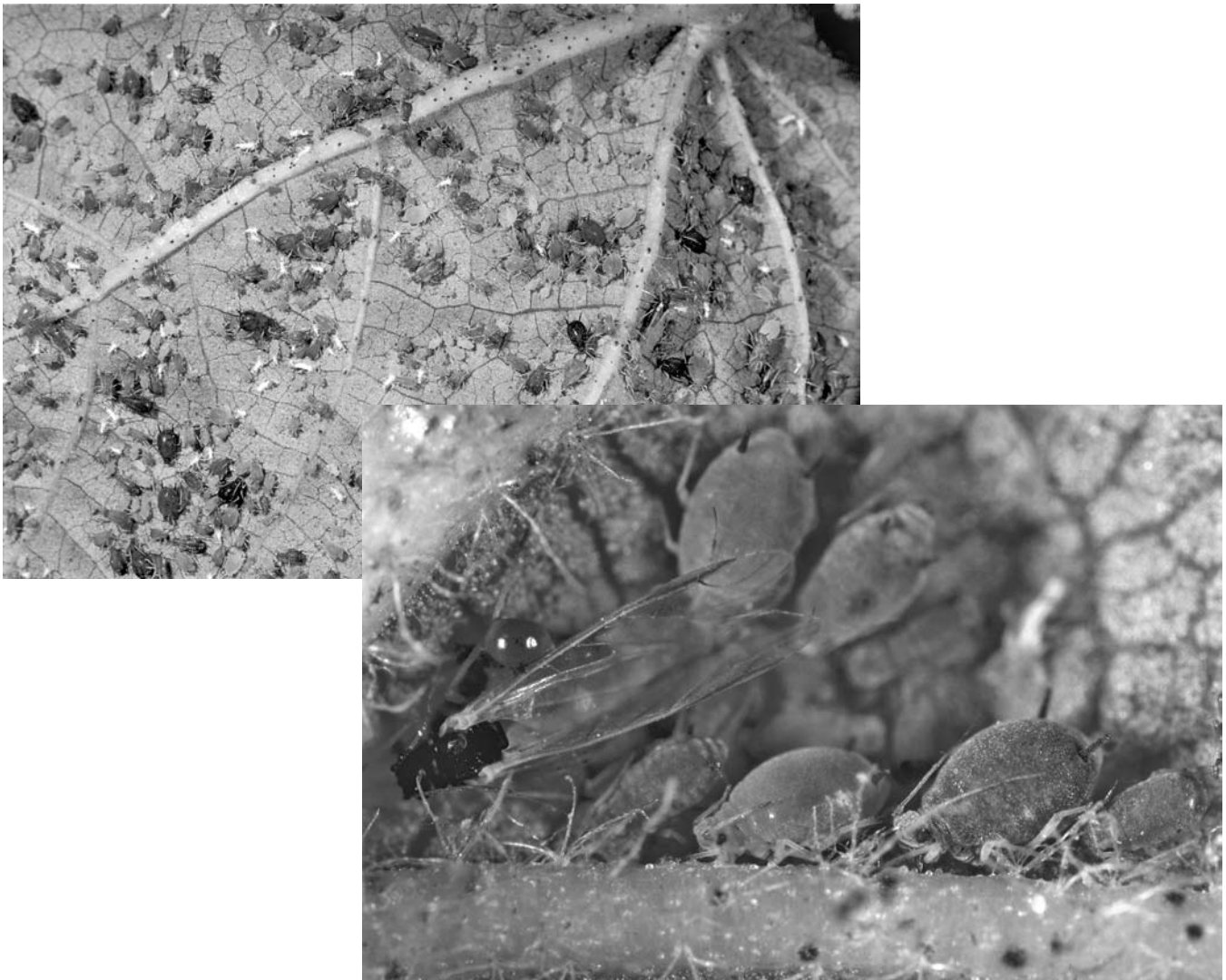


Figure 4. Cotton aphid color morphs.

predator numbers could be manipulated with a relay cropping strategy to increase predator abundance in cotton. In their relay intercropping study, aphid population increase was delayed and aphid numbers per leaf were lower compared to aphid populations in cotton isolated from relay crops. The actions of predators and parasitoids can generally regulate aphid populations effectively on pre-reproductive stage cotton in California (Rosenheim et al. 1997), but intraguild predation (predators preying on or disrupting the activities of other predator species) limits the utility of biological control of aphids during midseason in California (Rosenheim et al. 1993).

The fungal pathogen *Neozygites fresenii* (Nowakowski) has been an effective biological control agent infecting cotton aphids in Mid-South cotton since 1988, and epizootics in Arkansas occur from mid July to mid August (Steinkraus et al. 1995). In Mississippi, this pathogen can reduce aphid populations to near zero in early and late season, while the parasite *Lysiphlebus testaceipes* (Cresson) can cause cotton aphid populations to decline in early season (Hardee et al. 1994). *Neozygites fresenii* has been introduced and researched in California, but the fungus has not become widely established (McGuire et al. 2001).

## Cultural Management

In the Texas Rolling Plains, cotton can be planted from late April to late June. Aphid numbers during August have been consistently highest on cotton planted in late June. While aphid numbers are generally low during August on cotton planted in late April, regrowth after all bolls are set can lead to very high numbers of aphids in late August and early September. The optimum planting time to minimize aphid abundance is between mid May and mid June (Slosser et al. 1992a, Slosser et al. 1998). Changes in the cotton agro-ecosystem and cultural practices were theorized to be part of the explanation for the increased importance of cotton aphids in California in recent years. Higher aphid populations have consistently been seen on late-planted (May) than on early-planted (April) cotton. Higher levels of nitrogen in the late-planted cotton at some key point (for aphid buildup) in the season appear to be involved in this increase in aphid levels.

In a nitrogen fertility study in Texas, nitrogen was applied at planting to dryland-grown cotton at rates of 0, 32, 62, or 88 lb/acre (0, 36, 69, 99 kg/ha). Percentage of leaf nitrogen was positively correlated with nitrogen

applied at planting ( $r = 0.934$ ,  $P = 0.066$ ,  $n = 4$ ) for the late May planting date, and there was a positive linear correlation between aphid numbers and leaf nitrogen during August only for the late May planting date ( $r = 0.877$ ,  $P = 0.123$ ,  $n = 4$ ). Nitrogen fertility levels of 62-88, 32-62, and 0-32 lb/acre were recommended for cotton planted in late April, late May, and late June, respectively. These levels provided acceptable yields in each planting date without increasing the severity of cotton aphid infestations. The reduced nitrogen inputs for planting dates in May and June, compared to April, were justified since yields also decreased for the later planting dates (Slosser et al. 1997a).

It was a common practice in California to limit cotton vegetative growth through deficits of nitrogen and irrigation; however, with the advent of plant growth regulators to control growth these agronomic inputs are no longer used in limiting amounts. In 1997, aphid populations averaged about 300 per leaf on plants fertilized with nitrogen at 200 lb/acre (224 kg/ha) and 75 per leaf on plants receiving 75 lb/acre (84 kg/ha). Studies in 2000 showed that cotton aphid populations were consistently higher with each increase in nitrogen application rate from 0 to 280 kg/ha (figure 5). Aphid densities were monitored from 1998 to 2000 in 22 large-plot nitrogen response tests in grower fields, and higher aphid numbers were seen in all 15 locations with discernible differences between aphid populations in the 200 lb/acre (224 kg/ha) vs. 50 lb/acre (56 kg/ha) treatments (Godfrey et al. 2000b, 2001b). Results with 100 and 150 lb/acre (112 and 168 kg/ha) were less decisive, but generally there were more aphids after the higher nitrogen application rates.

Detailed studies on cotton aphid fitness have been conducted to delineate the effects of nitrogen on aphid populations. Generation times of aphids from a laboratory colony out-planted into field cages ranged from 7.1 to 7.9 days, and the number of offspring per adult averaged 18.5 and 44.1 under 0 and 250 lb/acre (0 and 280 kg/ha) nitrogen regimes, respectively (Cisneros and Godfrey 2001a). Survival was not consistently related to the nitrogen treatment. Elevating potassium levels (applying 150 lb of potassium sulfate [168 kg/ha]) had a moderate negative effect on both generation time and fecundity of the aphids. Similar patterns were observed with the second and third aphid generations.

These changes in aphid fitness at the individual level may explain, in part, the effects of nitrogen fertility

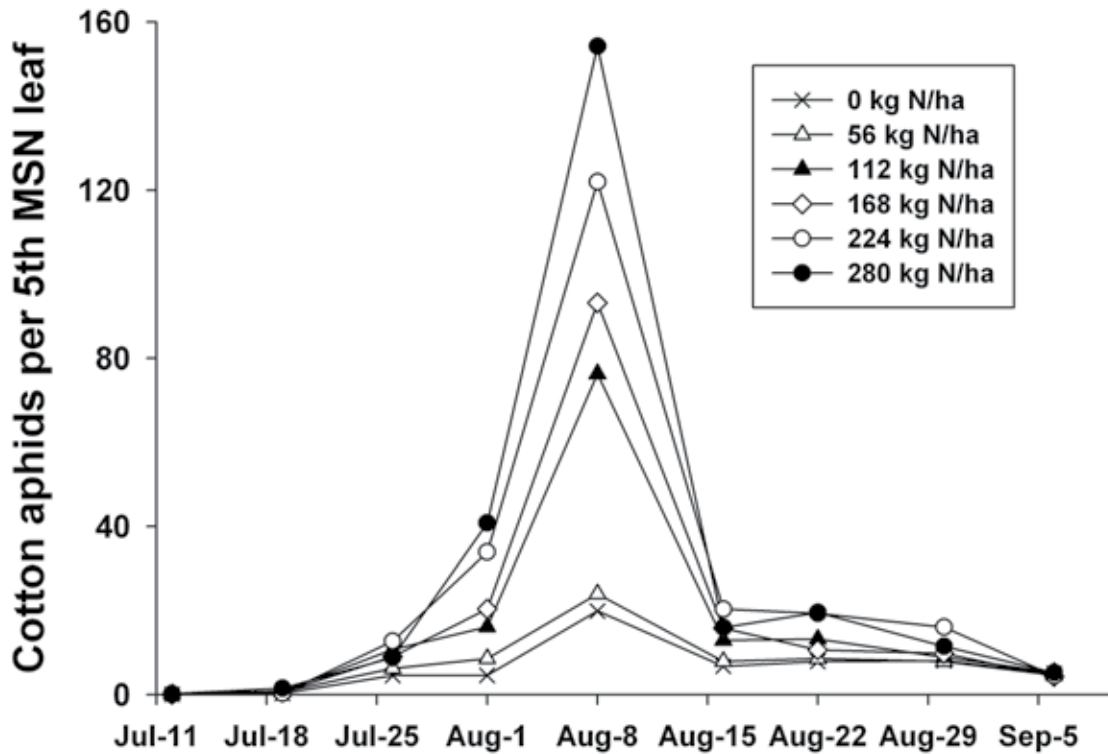


Figure 5. Influence of nitrogen rate on cotton aphid population dynamics. Shafter, California, 2000. In the 0 kg treatment, residual N in soil was 9 kg/ha, and the other treatments were adjusted for this residual.

at the population level observed in the field. Field population levels in this study reinforced the field cage data. Aphid densities peaked on August 8, and peak numbers ranged from 19.9 aphids per leaf (0 lb/acre N) to 154.2 aphids per leaf (250 lb/acre). Plots with elevated levels of potassium averaged 100 to 120 aphids per leaf (at 200 lb/acre N). Similar results were shown from studies conducted in 1999: The influence of elevating potassium concentrations was more apparent, and overall aphid fecundity was about 50 percent lower in 1999 than in 2000. Environmental (or other) effects apparently mediate the response to nitrogen. Nevo and Coll (2001) reported that adult and nymph densities and intrinsic rate of increase were positively correlated with increasing levels of nitrogen fertility, and aphid fecundity was influenced by host plant nutritional quality of the parental generation.

Rummel et al. (1995) reported lower aphid numbers in plots with a wheat straw mulch than in plots with bare soil. Wheat straw mulch retarded aphid population development, apparently because the wheat straw mulch reflected more radiant energy than the bare soil control, increasing light intensity on the underside of the cotton leaves.

Leaf pubescence and leaf color have a significant influence on cotton aphids (Rummel et al. 1995). Aphid numbers tended to be lower on plants with smooth leaves and higher on pilose leaves. Aphid numbers tended to be lower on cotton with red and yellow leaves than on cotton with green leaves. Weathersbee and Hardee (1994) also reported that cotton aphids were less abundant on smooth (glabrous) leaf cultivars and more so on pubescent cultivars. These workers concluded that host plant resistance to cotton aphids was associated with the smooth-leaf character. No significant differences were seen among the California-approved Acala cottons in terms of aphid numbers or leaf pubescence (Leigh et al. 1994). Observations have shown higher aphid numbers on Pima cotton than on Acala cotton in adjacent plots.

Rummel et al. (1995) reported that cotton aphid infestations were significantly affected by plant density. They found that number of aphids per leaf increased as number of plants per foot of row decreased: Aphid numbers were 2.4 times higher in stands of 0.5 plant per row foot (0.3 m) than in stands of 6.0 plants per row foot. Parajulee et al. (1999) compared aphid infestations in cotton planted in every row with skip-

row planting patterns of plant two rows, skip one row (2×1) and plant two rows, skip two rows (2×2). Aphid numbers per leaf were significantly higher in the 2×2 skip-row planting pattern than in solid-planted cotton, while numbers in the 2×1 skip-row pattern were intermediate.

Applications of broad-spectrum insecticides often play a role in buildup of aphid populations. Field applications of pyrethroid, organophosphate, and carbamate insecticides have been shown to increase aphid levels in some cases (O'Brien and Graves 1992, Brown and Reed 1992), although this is most commonly with pyrethroids. Pyrethroid insecticide applications can be quite detrimental to populations of several species of natural enemies. This disruption of natural enemy populations can be part of the explanation for aphid population increases. However, aphid populations can be increased on a very small scale by applications of pyrethroids to single plants, which partially negates the effects on mobile predators. Aphid populations increased by 7.2, 32.1, and 57.8 times on untreated, bifenthrin-treated, and cyfluthrin-treated plants, respectively, over a 15-day period (Godfrey et al. 2000b, 2001b). Kidd et al. (1996) demonstrated that cyhalothrin stimulated cotton aphid population increase, and the increase in aphid numbers did not appear to be related to reductions in predator populations. Parajulee and Slosser (2001) reported that net reproductive rate was higher for aphids reared on cyhalothrin-treated leaves than on untreated cotton leaves, indicating a possible trophobiotic role of cyhalothrin on aphid population outbreaks.

Nitrogen fertilizers and pyrethroid insecticides appear to interact synergistically on aphid populations (Godfrey et al. 2000b, 2001a,b). Pyrethroid insecticides are commonly used for western tarnished plant bug (*Lygus hesperus* Knight) management at the same time as the initiation of cotton aphid infestations. Natural aphid populations were monitored in plots in 1999 and 2000; at the onset of aphid buildup in plots with 20, 50, 100, 150, and 200 lb/acre nitrogen (22, 56, 112, 168, and 224 kg/ha), an application of either bifenthrin, imidacloprid, or no insecticide was superimposed. Three weeks later, in the untreated plots aphid numbers responded slightly across the increasing nitrogen levels (6 to 31 aphids per leaf from 20 to 200 lb/acre). Imidacloprid reduced aphid numbers significantly during both years, which is in agreement with its activity spectrum. However, at 100 and 150 lb/acre of nitrogen, the aphid population in the bifenthrin-

treated plots was about twice the size of that in the untreated plots; and at 200 lb/acre, there were four to six times as many aphids in the bifenthrin-treated plots than in the untreated plots. Nitrogen level within the plant influences aphids' susceptibility to insecticides, and McKenzie et al. (1995) reported that cotton aphids were more susceptible to methomyl at lower leaf nitrogen levels.

Slosser et al. (1997b) reported that dicotophos was less effective for controlling cotton aphids in cotton planted in late June than in cotton planted in late April and late May. Nutritional quality of the plant, as influenced by plant maturity, regulates the reproductive potential of the aphids. Maturing plants (planted in late April and late May) hinder reproduction, making dicotophos more effective, while immature plants (planted in late June) enhance aphid reproduction, making dicotophos less effective. Cotton planted in late June had higher leaf nitrogen levels than cotton planted in late April and late May. Clonal cotton aphids, which developed on plants fertilized with nitrogen at 200 lb/acre (224 kg/ha), were more resistant to bifenthrin, endosulfan, chlorpyrifos, carbofuran, and imidacloprid (insecticides from five different chemical classes) than aphids feeding on plants fertilized at 50 lb/acre (56 kg/ha) (Cisneros and Godfrey 1998). The higher levels of nitrogen affected the phenotypic response of the aphids and resulted in a higher number of dark-colored morphs, which were shown to be incrementally more resistant to these insecticides than light-colored morphs produced on the same plant. Choice of insecticides and amount of nitrogen fertility need to be carefully considered to avoid stimulating reproduction and production of dark-colored morphs, which have higher reproductive rates than light-colored morphs (Rosenheim et al. 1994) and can be resistant to some insecticides.

### **Late-Season Management**

When cotton aphid populations develop in late season during boll opening, exposed lint becomes contaminated with honeydew. Several crop management practices can contribute to development of unacceptable levels of cotton aphids during crop maturation in the Texas Rolling Plains (Slosser et al. 2001). An application of cyhalothrin for control of bollworm (*Helicoverpa zea* (Boddie)) coupled with an irrigation in late August can stimulate development of high numbers of aphids during September during boll opening. An application of ethephon, a chemical



used to enhance boll opening, also resulted in higher aphid numbers compared to numbers in untreated plots. Application of pyrethroid insecticides, such as cyhalothin, and irrigation in late season, both of which enhance aphid reproduction, should be avoided when bolls begin to open to reduce the risk of lint contamination by aphid honeydew. Some aphicides such as pymetrozine are less effective for controlling cotton aphids when leaf moisture is enhanced by irrigation.

## Summary of Management Recommendations

**Planting date:** Plant as early as practical or use recommended optimum planting dates; expect increased aphid problems in late-planted cotton.

**Fertility:** Match nitrogen fertility to realistic yield goals and avoid excessive nitrogen and use adequate potash ( $K_2O$ ) for cotton needs; expect increased aphid problems in situations with an abundance of nitrogen fertilizer (including residual carryover in the soil).

**Variety:** Plants with glabrous (smooth) leaves have fewer aphids than plants with pilose (hairy) leaves; expect more aphid problems on Pima cotton.

**Plant density:** Thin stands, skip-row planting, and stands with skips within the row have higher aphid population levels than uniform stands.

**Insecticide selection:** Attempt to minimize the number of broad-spectrum insecticide (pyrethroids, organophosphates, carbamates) treatments used to control all cotton pests, and alternate insecticide applications among materials from different classes. Use pyrethroids for *Lygus* management only under conditions of heavy pressure and sustained migration. To conserve natural enemies, avoid early-season use of pyrethroids and other broad-spectrum insecticides. Some insecticides are less effective on plants with high leaf moisture and nitrogen content (immature plants).

**Thresholds:** Do not treat presquaring aphid infestations unless the infestation persists for 14 days or longer. From squaring to first open bolls, delay treatment until infestations exceed 50 per leaf for at least 7 days. After boll opening, infestations as low as 10 per leaf can cause sticky lint problems.

**Late Season:** Manage the crop for earliness and terminate and harvest in a timely manner; avoid late-

season irrigations that would stimulate regrowth after physiological cut-out.

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## Chapter 8

### **Crop Production Inputs, Cultural Control, Sweetpotato Whitefly Populations, and Sticky Cotton**

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The cotton lint honeydew contamination problem appears to be most effectively solved by reducing the numbers of honeydew-producing insects. Highly effective insecticide control technology has been developed and presented in chapters 6 and 7 in this volume. Other crop production management techniques can also contribute significantly to reducing sweetpotato whiteflies and ameliorating the development of sticky cotton. In this chapter, we consider the effects of cotton crop production inputs, crop termination, and optimum harvest scheduling to minimize late-season sweetpotato whitefly population development and sticky cotton.

#### **Crop Production Techniques**

##### **Cotton Cultivars**

Although the mechanisms of cotton plant resistance are not known, differences in susceptibility between upland cottons and between upland and Pima cottons to sweetpotato whiteflies have been well documented (Natwick et al. 1995, Percy et al. 1997, Henneberry et al. 1998, Chu et al. 2000). Genotypes with smooth-leaf characteristics generally have lower populations than hairy-leaf cottons (Butler and Henneberry 1984, Flint and Parks 1990, Butler et al. 1991, Norman and Sparks 1997). Okra-leaf genotypes are generally more resistant than normal-leaf genotypes (Berlinger 1986, Chu et al. 1999). Higher temperature and lower humidity environments of okra-leaf cotton have been considered as less suitable sweetpotato whitefly habitats (Sippell et al. 1987), possibly accounting for reduced insect populations. Another hypothesis suggests that the more open okra-leaf canopy affords more effective insecticide penetration, which improves control efficacy (Khalifa and Gameel 1982).

In addition to differences in leaf shape and morphology, particularly trichomes and trichome density (Chu et al. 2000), differences in crop phenology for upland and Pima cottons are major considerations in sweetpotato whitefly management and sticky cotton development. Numbers of open mature cotton bolls

are higher earlier in the season in upland cottons than in Pima cotton (Henneberry et al. 1998). Numbers of open bolls for upland cotton peak 8 to 14 days earlier than in Pima cotton. Clear-cut termination of open boll production in upland cottons results in 95 percent or higher of the total crop produced by mid September, compared with 80 percent for long-staple cotton. These crop maturity patterns clearly show the value of incorporating this information into the decision-making for irrigation termination and preharvest defoliations when sticky cotton is a threat.

##### **Water Management**

Sweetpotato whitefly populations develop to higher levels on cotton plants under water stress than on well-watered plants. Increased numbers of nymphs following irrigation termination in Israel has been partially explained by increased nymph survival on water-stressed cotton leaves (Mor 1987). Flint et al. (1992) reported similar results in Arizona in both Pima and short-staple cottons. The mechanisms inducing population increases remain unexplained but may be the result of physiological changes in the cotton plant resulting from decreased leaf water potential (Mor 1987). Populations of eggs, nymphs, and adults can be reduced by 22 to 69 percent in cotton furrow-irrigated weekly compared to populations on cotton plants irrigated every other week (Flint et al. 1996). Daily drip-irrigated cotton averaged about 50 percent fewer immature sweetpotato whiteflies than plants irrigated with the same amount of water applied biweekly (Flint et al. 1994a,b, 1995, 1996). The number of nymphs was consistently about one third of the number of eggs on the same leaf, regardless of irrigation treatment. It appears that the higher numbers of immatures on water-stressed cotton results from higher adult populations and increased egg laying.

##### **Fertilizer Management**

Sweetpotato whiteflies in laboratory studies have been reported to generate less honeydew on cotton plants given a high-nitrogen fertilizer regime than on those given a low-nitrogen regime (Blua and Toscano 1994). The results were explained by the authors as resulting from sweetpotato whiteflies ingesting greater volumes of plant sap from low-nitrogen-content plants to maintain nitrogen intake than from plants fertilized with high doses of nitrogen. The authors did not find differences in the survival of the various sweetpotato whitefly life stages feeding upon cotton plants given various dosages of nitrogen. However, the time from egg to adult emergence increased with decreasing

plant nitrogen fertilization. Prabhaker et al. (1999) found sweetpotato whiteflies laid fewer eggs on plants produced from urea-treated seeds. However, adding urea to the soil had no effect on egg laying, suggesting that the effect was not simply a result of changes in plant nitrogen status. Under field conditions, numbers of sweetpotato whitefly adults and immatures increased during population peaks with increasing amounts of applied nitrogen (Bi et al. 2001). More honeydew was deposited by increased sweetpotato whitefly numbers.

Explanations for the role of nitrogen in increasing sweetpotato whitefly populations vary and include production of plant growth resulting in larger, more vegetative plants that provide better sweetpotato whitefly habitat (Joyce 1958, Hassan 1969, Jackson et al. 1973, Abdelrahman and Saleem 1978). Cotton petiole glucose levels were significantly correlated to sweetpotato whitefly adult numbers, but other cotton physiological parameters were not significantly related (Bi et al. 2001). Hector and Hodkinson (1989) note the potassium-nitrogen interactions in which high levels of potassium fertilization may limit nitrogen in plant sap and hypothesize a possible relationship to sweetpotato whitefly populations. Skinner and Cohen (1994) added to the complexity of the fertilizer-whitefly relationship by noting the water stress increases infestations, but nitrogen and phosphorus deficiencies (Sundaramurthy 1992) induce water deficiency in cotton by reducing root hydraulic conductivity (Radin and Eidenbock 1984). Phosphorous deficiency in cotton causes fewer eggs to be laid on true leaves, but not on cotyledons. Host acceptance was correlated to low leaf sucrose, but not amino acid or amino acid-sucrose ratios. Skinner and Cohen (1994) suggested that host selection was based on minimizing osmotic stress rather than maximizing amino acid ingestion.

### **Plant Growth Characteristics**

Planting dates, row spacing, irrigation, plant density, and other variables in cotton production that influence plant growth, development, and crop maturation probably in some direct or indirect way have the potential for influencing sweetpotato whitefly population dynamics. However, results with 25,000 and 100,000 cotton plants per hectare did not show any significant influence on sweetpotato whitefly or sticky cotton development (Henneberry et al. 1998). Thus, reports have been highly variable, and specific recommendations for manipulating crop production inputs, except for water management, are without sufficient documentation to support implementation

(Hector and Hodkinson 1989). These are researchable areas and the nature, extent, and scope of the lint stickiness problem justifies intense efforts to explore the possibility of exploitable cotton production inputs that could make cotton ecosystems less susceptible to sweetpotato whitefly infestations.

### **Plant Diversity**

The numerous hosts of the sweetpotato whiteflies have been discussed by many authors. More than 500 plant species have been reported attacked by whiteflies. Hosts range from numerous weed species to cultivated crops and ornamentals, providing a continuity plant biomass that supports sweetpotato whitefly reproduction throughout the year in many parts of the world. Destruction of weed hosts in agricultural and urban areas, along roadsides, in fence rows, and the like has been recognized as a useful management practice (Hector and Hodkinson 1989). Typical sequential crop production systems in many parts of the world have been recognized as particularly advantageous to sweetpotato whitefly bionomics and have been manipulated to break the host-sequence cycles. These approaches have been proven to be highly effective contributions in areawide community action programs. For example, in Israel annual squash, tomato, bean, and cucumber crops are planted in sequence and in close proximity and often close to the perennial eggplant crop (Sharaf et al. 1985). This planting sequence was shown to significantly aggravate the sweetpotato whitefly problem. Reductions in populations were achieved by planting cucumbers a month earlier than tomatoes, squash, and beans and spatially isolating squash, bean, and eggplant crops from cucumber plantings. Further advances in sweetpotato whitefly management were achieved by growing eggplants as an annual crop instead of perennially.

Breaking the host plant cycle has been accomplished in a different, but equally effective, manner in Arizona and California. The typical crop production cycle in these states is spring melons, cotton, fall melons, and winter vegetables and cole crops. The highly effective systemic neonicotinoid insecticide imidacloprid, used for sweetpotato whitefly control in melons and vegetables, has broken the sequential host plant link from spring melons to cotton and from cotton to melons and vegetables in the fall (Palumbo et al. 2001).

## Conventional Insecticide Crop Protection

### Seasonal Population Development

Generally, sweetpotato whitefly adult populations in untreated cotton fields remain low early in the season (June and early July) followed by increases to economic numbers in mid to late July (figure 1A). Eggs (figure 1B) and nymphs (figure 1C) follow a similar growth pattern, but increases generally lag 8 to 10 days behind the adult population. The accumulation of the sweetpotato-whitefly-produced honeydew sugars, trehalulose and melezitose, in untreated cotton lint closely follow the populations increases (table 1).

### Chemical Control

A number of different chemical insecticides have been demonstrated to effectively control sweetpotato whiteflies (Ellsworth et al. 1996, 1997). Chemical control approaches and resistance management are discussed in detail in chapters 6 and 9. In this chapter we focus on the effect of chemical control on reduced cotton lint stickiness of harvested cotton. Conventional insecticide applications (figure 1), initiated when counts reach 10 adults per leaf, keep the seasonal average populations below economic thresholds ( $\leq 3$  to 5 eggs and nymphs per  $\text{cm}^2$  of leaf disk). Sweetpotato whitefly sugars extracted from lint and the associated sticky cotton thermodetector (SCT) sticky cotton counts can also effectively be held below thresholds ( $\leq 5$  sticky spots per 2.5-gram cotton lint sample) by these treatments (Henneberry et al. 1995, 1996, 1997, 1998). In the example given, the average numbers of sweetpotato whitefly adults and nymphs for sampling dates during boll opening (August 14 to September 5) were significantly correlated with SCT counts for cotton lint harvested on September 20. The regressions of SCT counts on the average numbers of adults per leaf turn ( $Y = 4.89 + 0.84X$ ;  $r^2 = 0.51$ ;  $P = 0.01$ ) and nymphs per square centimeter of leaf disk ( $Y = 4.28 + 0.42X$ ;  $r^2 = 0.58$ ;  $P = 0.01$ ), also were highly significant ( $F = 38.91$  and  $F = 62.86$ ;  $df = 1,45$ ;  $P = 0.01$ , respectively). SCT counts were 5 for cotton lint stickiness at 11.8 adults per leaf turn (see chapter 6) or 1.7 nymphs per square centimeter of leaf disk. The amount of trehalulose and melezitose per gram of cotton lint were highly correlated with the mean number of sweetpotato whitefly adults ( $r = 0.68$ ;  $n = 46$ ;  $P = 0.01$ ). The amounts of trehalulose and melezitose per gram of cotton lint, in each case, also were significantly correlated to lint thermodetector counts ( $r = 0.60$ ;  $n = 46$ ;  $P = 0.01$ ).

## Late-Season Crop Management, Irrigation Termination, and Defoliation

Careful water management, as discussed above, to avoid the plant stress that encourages high sweetpotato whitefly populations during the season is an excellent management practice. Chemical control and water management for sweetpotato whitefly management may conflict with late-season preparations to terminate the crop, defoliate, and harvest cotton at the end of the season. Thus, even though careful attention to sweetpotato whitefly control is carefully followed during the early and mid season (the first fruiting cycle), carrying the crop into the second fruiting cycle without continuing crop protection carries a high degree of risk for developing sticky cotton lint late in the season. In late season, when most of the cotton bolls are mature and open, sweetpotato whitefly populations increase prior to defoliation and sticky cotton can develop in 2 to 3 weeks if the plants are unprotected (Henneberry et al. 1998). Alternatively, irrigation termination in late August to allow cotton defoliation by September 15 avoids insect honeydew exposure when most of the first fruiting cycle bolls are open. Timing of the last irrigation and the application of defoliant in relation to the last insecticide protection to avoid increases in sweetpotato whitefly populations late in the season are also important tools in management of the cotton crop to avoid sticky cotton (Henneberry et al. 1998).

## Overhead Irrigation and Lint Stickiness

Efforts to wash honeydew from lint of open cotton bolls in the field using overhead sprinkler irrigation have produced variable results. In California, sprinkler irrigation was reported to have little effect on cotton lint contaminated with cotton aphid honeydew, but 1.8 cm of rain dramatically reduced stickiness of harvested cotton (Rosenheim et al. 1995). In contrast, workers at the Beth Shean Valley Experiment Station in Israel found that sprinkler irrigation was effective for reducing lint stickiness resulting from sweetpotato whitefly infestations (Fishler 1986). Similarly, Newton et al. (2000) in Texas found that above-canopy sprinkler irrigation effectively reduced the lint stickiness as measured using the high speed stickiness detector (H2SD). Approximately 2.5 cm of overhead irrigation reduced the total sticky counts below the critical threshold level ( $Y = 4.5 X^2 - 89.3X + 48.0$ ;  $R^2 = 0.98$ ; where  $Y = \text{H2SD counts}$  and  $X = \text{applied water}$ ). In Texas, three applications of 64,000 L/ha of water using center-pivot overhead irrigation appeared

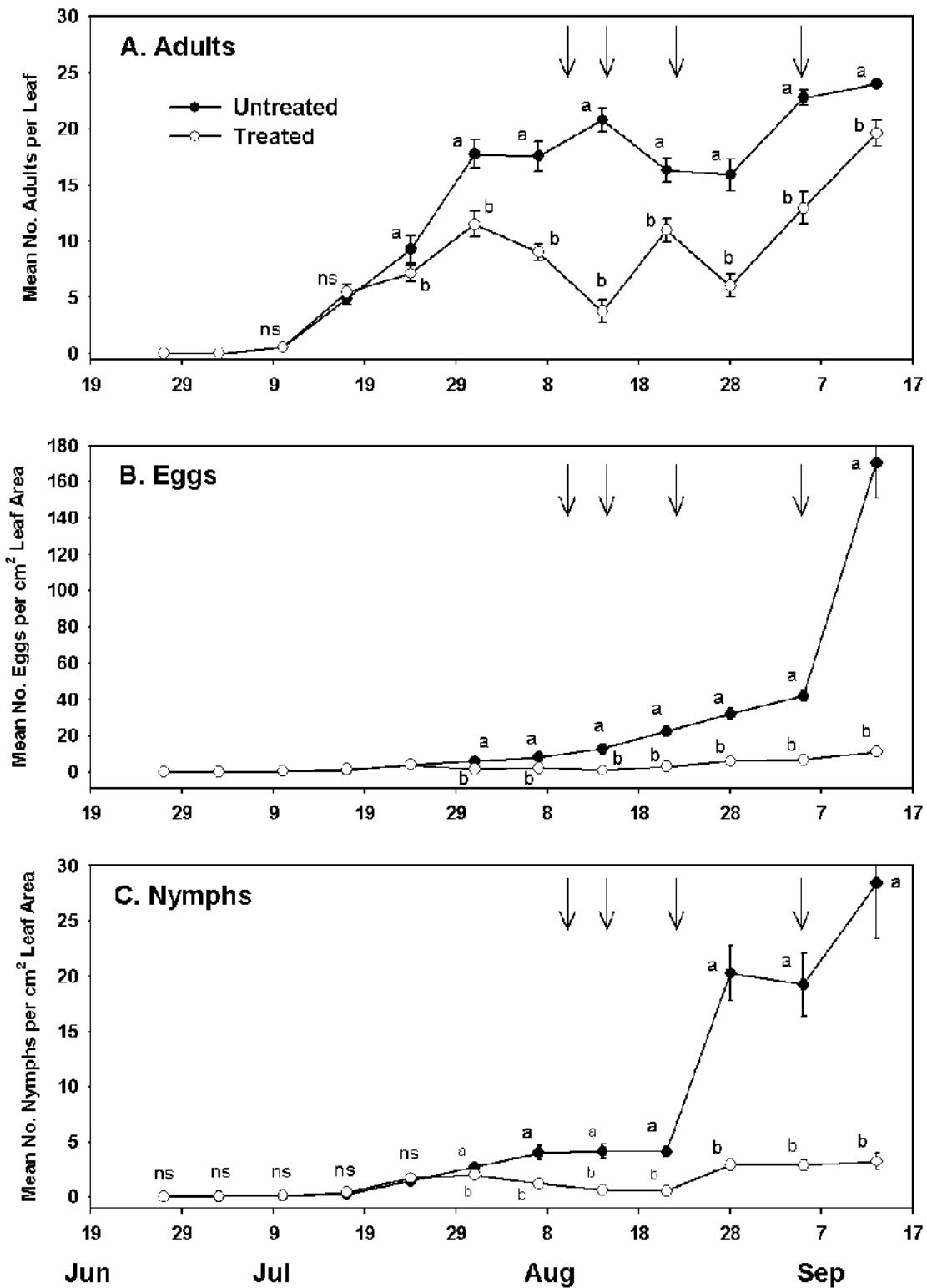


Figure 1. Mean numbers of *B. tabaci* adults per leaf turn and eggs and nymphs per cm<sup>2</sup> of leaf disk from untreated and insecticide-treated cotton plots. Means not annotated by the same letter are significantly different. Arrows indicate rainfall. (Modified from Henneberry et al. 1998).



to reduce H2SD-determined lint stickiness from cotton aphid honeydew to acceptable levels (Arnold et al. 2002).

## Discussion

Standardized crop production methodology and chemical control use patterns in community-wide sweetpotato whitefly management systems have been highly effective. There are many additional methods included in integrated management programs for sweetpotato whitefly control on cotton. Reliance on any single control option is high-risk and has a low probability of long-term success. Smooth-leaf varieties generally support lower sweetpotato whitefly populations than hairy-leaf cottons. Optimum yield

goals that support early and uniform plantings with early termination and harvest are encouraged to reduce days of lint exposure to honeydew-producing insects. During the season, water management to avoid cotton plant stress and fertilization schedules (particularly of nitrogen) that encourage vegetative growth are to be avoided. Early harvest and destruction of crop residues prevents development of additional sweetpotato whitefly generations that would disperse to other crops. Host-free periods between sequentially planted susceptible crops are to be encouraged for as long as possible. Equally important is crop spacing and avoidance of proximity to additional hosts. These goals and others for managing sweetpotato whiteflies and managing the crop to reduce potential for sticky cotton development are in various stages of development.

**Table 1. Trehalulose and melezitose on cotton lint and thermodetector counts for untreated and insecticide-treated cotton plots**

[Four replications; means on the same date in a column with two observations per replication not followed by the same letter are significantly different.  $P < 0.05$ ]

Sample date and treatment	<i>Bemisia</i> sugars		Thermodetector counts
	Trehalulose	Melezitose	
	.....mg/g .....		
August 29			
Untreated	0.90 a	0.36 a	8.67 a
Treated	0.23 b	0.21 b	3.08 b
September 5			
Untreated	1.34 a	0.43 a	12.71 a
Treated	0.22 b	0.03 b	2.83 b
September 13			
Untreated	1.83 a	0.47 a	13.00 a
Treated	0.23 b	0.16 b	2.38 b
September 20			
Untreated	2.28 a	0.59 a	13.17 a
Treated	0.45 b	0.26 b	3.75 b

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## Chapter 9

### Managing Insecticide Resistance in Whiteflies and Aphids in Cotton Fields

A.R. Horowitz, I. Denholm, and R.L. Nichols

Sweetpotato whiteflies and cotton aphids are relatively new as economically important cotton pests and have risen to increasingly higher levels of importance over the last 20 to 30 years in many of the arid crop production areas. Although some natural biological control has been achieved, the use of insecticides remains the primary strategy for control in cotton fields.

In many cropping systems, repeated insecticide applications to control sweetpotato whiteflies and cotton aphids often result in development of resistance (Dittrich et al. 1990, Denholm et al. 1996, Grafton-Cardwell et al. 2000, Herron et al. 2001, Palumbo et al. 2001). Use of diverse insecticide classes can delay or prevent resistance (as in Horowitz and Ishaaya 1996). Newly developed insecticides such as the neonicotinoids pymetrozine and diafenthiuron are effective against whiteflies and aphids (Ishaaya and Horowitz 1998), although aphids in cotton fields are still controlled primarily by conventional insecticides (such as organophosphates, carbamates, and pyrethroids).

This paper reports on the status of insecticide resistance in sweetpotato whiteflies and cotton aphids along with insecticide resistance management tactics against these pests.

#### Overview of Resistance Mechanisms

Insecticide resistance is an evolutionary genetic phenomenon caused by a variety of mechanisms based on detoxification of insecticides or modifications to their arthropod target sites. Many such mechanisms are described in detail in several books and conference proceedings (see, for instance, Otto and Weber 1990, Roush and Tabashnik 1990, Mullin and Scott 1992,

Brown 1996, McKenzie 1996, Denholm et al. 1998b, Ishaaya 2001). Other recent reviews focus on specific resistance mechanisms such as cytochrome P-450 monooxygenases (Scott 1999, 2001) or on known mechanisms of resistance in important multiresistant pests such as the heliothine bollworms (McCaffery 1998).

The most extensively used insecticide classes—organochlorines, organophosphates, carbamates, and pyrethroids—have generally been the most seriously threatened by resistance and hence the major targets of research to resolve the causal mechanisms. Resistance to cyclodienes (such as dieldrin and endosulfan) usually results from a modification of the target site, the GABA-gated chloride channel of postsynaptic nerve membranes. (GABA is  $\gamma$ -aminobutyric acid.) Resistance to organophosphates (OPs) and carbamates can arise through enhanced detoxification by cytochrome P-450 monooxygenases, esterases, or glutathione-S-transferases, or from structural modifications of their target enzyme, acetylcholinesterase (AChE). Pyrethroid resistance can arise through enhanced esteratic or oxidative detoxification, as well as from target-site insensitivity at the voltage-gated sodium channel in nerve membranes (knockdown or *knr* resistance).

Mechanisms of resistance to insecticides acting outside the nervous system (such as insect growth regulators and *Bacillus thuringiensis* endotoxins) or to more novel neurotoxins (such as the neonicotinoids) are less clearly understood but are also likely to prove attributable to enhanced detoxification or target site modification.

Perhaps the most significant recent progress in understanding resistance mechanisms has resulted from the application of molecular biology to resistance research. Depending on the mechanism involved, resistance has been shown to arise through structural alterations of genes encoding detoxifying enzymes (Newcomb et al. 1997) or target-site proteins (Ffrench-Constant et al. 1998) or through processes (such as amplification or altered transcription) that affect gene expression (Hemingway et al. 1998). Despite the complexity of receptors or enzymes responsible, mutations leading to resistance frequently recur in different species (Thompson et al. 1993, Martinez-Torres et al. 1997). This is especially the case for mechanisms based on decreased sensitivity of insecticide target sites. Molecular studies of insecticide resistance have identified the point mutations

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associated with target-site insensitivity in genes encoding the three major insecticide targets: the GABA receptor (cyclodiene resistance), the voltage-gated sodium channel (pyrethroids), and AChE (OPs and carbamates) (ffrench-Constant et al. 1993, Mutero et al. 1994, Williamson et al. 1996). These provide exciting insights into the homology of resistance mutations between species and the frequency with which they arise (ffrench-Constant et al. 1996, 1998).

One of the most difficult challenges in managing resistance is the frequent occurrence of several resistance mechanisms in the same pest individual or population. Such cases of multiple resistance are best documented for pests that have been exposed repeatedly and for long periods to a succession of insecticide types, leading to the accumulation of mechanisms with contrasting cross-resistance characteristics. Examples of such multiresistant cotton pests include sweetpotato whiteflies, cotton aphids, and heliothine bollworms (such as *Heliothis virescens* (F.) and *Helicoverpa armigera* (Hübner)).

### **Bioassays for Resistance Monitoring**

Accurate and regular monitoring of changes in susceptibility is essential for anticipating resistance problems and for assessing the effectiveness of resistance management tactics. It is highly advantageous to evaluate, define, and standardize test methods for insecticides, especially novel insecticides, prior to their introduction in the field. Monitoring tests should be as rapid and simple as possible, yield repeatable results, and be sensitive enough to detect any differences in tolerance under field conditions (Denholm et al. 1998b).

Monitoring programs to detect resistance genotypes and phenotypes as early as possible and to document their distribution should be a key component of any resistance management strategy. Whole-organism bioassays, involving topical application or exposure to pesticide residues on surfaces or in food, have long been the basis of such programs but are limited in their application (Roush and Miller 1986). Comparisons of LD<sub>50</sub> or LD<sub>90</sub> values of samples from populations—the most widely adopted approach—may be useful for detecting a high frequency of resistant insects but are far too insensitive for detection of incipient resistance. Use of a “discriminating” dose (or concentration) corresponding to the LD<sub>99</sub> or higher of baseline susceptible populations, although a better alternative, is

still subject to important statistical constraints. Firstly, the estimation of these doses is challenging because the fitting of probit models is usually inaccurate at the extreme ends of dose-response relationships. Secondly, unless doses are perfectly diagnostic (killing 100 percent of susceptible pests but no resistant pest, which is rarely the case), sample sizes required for the reliable detection of even 1 percent resistance may be very large (Roush and Miller 1986).

### **Monitoring for Resistance in Whiteflies**

There are several bioassay methods available for whiteflies (for example, see Ishaaya et al. 1988, Cahill and Hackett 1992, Prabhaker et al. 1996, 1997; Horowitz et al. 1998, Cahill and Denholm 1999, Castle et al. 1999). For adults, the most widely used bioassay is the leaf-dip test with numerous variations; the common principle is to expose adults (female or both sexes) either to a cotton leaf disk or a seedling that has been dipped in formulated insecticide solution. In the case of the leaf-disk method, the leaf may be excised and placed on a layer of agar in a petri dish (as in Horowitz et al. 1988, Cahill et al. 1995). With the seedling method, the adults are confined to the treated leaf using a clip cage (Ishaaya et al. 1988, Horowitz et al. 1994). Two other approaches of more limited utility involve confining adults inside glass scintillation vials coated with an insecticide deposit (Cahill and Hackett 1992, Prabhaker et al. 1996, Sivasupramaniam et al. 1997a) and trapping adults on yellow sticky cards impregnated with insecticide (Prabhaker et al. 1996). Lacking any source of food, both are suitable only for testing contact insecticides for short periods of time (3 hours, for example).

Methods for testing insecticides with novel modes of action (such as buprofezin and pyriproxyfen) that act primarily on developing stages rather than adults are based on dipping foliage infested with eggs or nymphs (example: Cahill et al. 1996d). Another variation is to confine adults to treated leaves and determine the accumulated mortality until pupation (Ishaaya et al. 1988, Ishaaya and Horowitz 1992). The systemic effects of imidacloprid have led to the development of an alternative method in which adults or nymphs are exposed to foliage treated with the insecticide either through plant roots or the petiole of an excised leaf (Cahill et al. 1996c, Horowitz et al. 1998). For testing the systemic effects of imidacloprid on whitefly adults, a hydroponic procedure has also been suggested (Williams et al. 1996, Prabhaker et al. 1997). A one-day hydroponic uptake procedure using cotton

seedlings and reliable mortality criteria was devised by Williams et al. (1996). Similar bioassay methods have been developed for other neonicotinoid insecticides (Horowitz et al. 1998).

In assay of two novel insecticides, diafenthiuron and pymetrozine, some problems arose. The toxicity of diafenthiuron against insects depends on desulfuration in the presence of light to a carbodiimide derivative (CGA 140408) that inhibits adenosine triphosphatase activity in mitochondria (Ruder et al. 1991). The poor repeatability encountered when testing this insecticide against sweetpotato whiteflies may be due to variable and inefficient photoconversion under laboratory lighting (Denholm et al. 1995). Repeatability was increased by conducting bioassays after exposing treated plants to sunlight (Ishaaya et al. 1993)

Pymetrozine is thought to act primarily by suppressing stylet penetration. The insecticide limits feeding by whiteflies and other homopteran pests, leading to their starvation (Kayser et al. 1994). Testing of pymetrozine against sweetpotato whiteflies and cotton aphids showed a holding period of at least 96 hours (and preferably 120 hours) to be essential for obtaining reliable dose-response data for whitefly adults or aphid nymphs (Denholm et al. 1995).

### **Monitoring for Resistance in Aphids**

As with whiteflies, leaf disc bioassays are used commonly in aphid studies. Typically, the pesticide is sprayed directly on groups of 20 adults on the leaf discs in the petri dishes (Herron et al. 2000, 2001) using a range of concentrations as well as discriminating treatment concentration (LC 99.9 value for a susceptible strain).

A rapid diagnostic bioassay was developed in the early 1990s and validated for use in assessing cotton aphids' susceptibility to insecticides on cotton (McKenzie et al. 1994, 1995). The bioassay was modified and used as a standard technique using either serial or discriminating concentrations (Fuson et al. 1995, Grafton-Cardwell and Goodell 1996, Grafton-Cardwell et al. 1997, Cisneros and Godfrey 1998, Grafton-Cardwell et al. 2000). The bioassay consists of adult aphids (20) placed in 50-mm petri dishes with the inner surfaces coated with different concentrations of the test insecticides. Mortality is determined after 3 hours of exposure.

### **In-Vitro Assays for Diagnosing Resistance in *Myzus persicae***

In-vitro assays for diagnosing the resistant genes or gene products are becoming feasible as alternatives to whole-organism bioassays. The advantages include more direct information on the genetic composition of a population and the potential for distinguishing between resistance heterozygotes and homozygotes. The latter is especially important in the early stages of selection when virtually all resistant alleles are present in heterozygous condition.

With sufficient background research, in-vitro assays can also be used to study multiple resistance mechanisms. This was demonstrated using *Myzus persicae* (Sulzer). Until recently, the resistance mechanism identified was overproduction of carboxylesterases that degrade or sequester insecticidal esters (Field et al. 1988). The mechanism was implicated in resistance to organophosphates and pyrethroids. Subsequent analysis of the *M. persicae* sodium channel gene for mutations associated with *kdr* resistance, coupled with supporting bioassays, has shown pyrethroid resistance to be attributable largely to the sodium channel gene mechanism (Martinez-Torres et al. 1999). Knockdown resistance had undoubtedly been present in aphid populations for many years but was overlooked because of lack of a suitable detection method. In 1990, a further resistance mechanism based on insensitive AChE was identified in southern Europe (Moore et al. 1994). The insecticide AChE mechanism confers resistance to pirimicarb, a carbamate, which had been the most effective chemical against high-esterase-based resistance and to triazamate, a novel aphicide that also inhibits AChE.

Collectively, the three mechanisms explain resistance to virtually all available chemicals (except the neonicotinoid imidacloprid). It is proving beneficial to be able to test for all three resistance mechanisms in aphid populations using a combination of bioassays, biochemical assays, and DNA diagnostics (Field et al. 1997). The methods are now being applied widely in the United Kingdom to study the dynamics of resistance and the interactions between different mechanisms and to provide recommendations for control strategies (Foster et al. 1998).

## **Current Status of Resistance in *Bemisia* and *Aphis gossypii***

### **Status of Insecticidal Resistance in *Bemisia***

Over the past 10 years a number of symposia, reviews, and book chapters have provided comprehensive details of the documentation, monitoring, and management of resistance in sweetpotato whiteflies and other whiteflies to conventional and novel insecticides (Dittrich et al. 1990, Cahill et al. 1996a, Denholm et al. 1996, 1998a, Horowitz and Ishaaya 1996, Cahill and Denholm 1999, Horowitz et al. 1999a, Palumbo et al. 2001). Therefore, our review briefly summarizes the recent reports of insecticide resistance in sweetpotato whiteflies.

### **Resistance to Conventional Insecticides**

Insecticide resistance in sweetpotato whiteflies involves all chemical groups. Dittrich et al. (1990) reviewed worldwide data on resistance in sweetpotato whiteflies to DDT, OPs, carbamates, and pyrethroids applied singly or as mixtures. The levels of resistance, with resistance ratios ranging sometimes from hundreds to thousands, were correlated with frequency and years of insecticide use. Resistance of this pest to conventional insecticides was observed in all countries in which monitoring was conducted (Horowitz and Ishaaya 1996).

### **Organophosphates (OPs) and Carbamates**

Dittrich et al. (1990) reported high resistance of sweetpotato whiteflies to monocrotophos, dimethoate, and methamidophos and lower resistance to profenofos in Turkey and the Sudan. Other studies in the United States reported resistance to chlorpyrifos and monocrotophos to be lower than that to methylparathion and sulprofos (Prabhaker et al. 1985). More recently, OP resistance was shown to be geographically widespread (Cahill et al. 1995) and attributable in part to modified acetylcholinesterase, the target site of these insecticides (Byrne et al. 1994, Byrne and Devonshire 1997). Metabolic mechanisms such as mixed-function oxidases and elevated carboxylesterases may also contribute to OP resistance in some populations (Denholm et al. 1996).

### **Pyrethroids**

Pyrethroid resistance in whiteflies is also widespread, although the magnitude and pattern of resistance and cross-resistance varies considerably among countries and cropping systems (Cahill et al. 1995, 1996a; Denholm et al. 1996). Intensive use of pyrethroids

in Sudanese cotton against sweetpotato whiteflies caused resistance to cypermethrin and deltamethrin to increase from 3-fold to about 170- and 350-fold, respectively, in the mid 1980s, although resistance to bifenthrin remained low. Subsequent reductions in pyrethroid use led to a corresponding decline in resistance levels (Dittrich et al. 1990). However, recent studies have shown high levels of resistance in Pakistan encompassing both bifenthrin and the older pyrethroids (Cahill et al. 1995). Pyrethroid resistance has also been observed in glasshouse or greenhouse populations from the United Kingdom, Netherlands, and Spain and from field crops in Israel, Turkey, and Cyprus (Cahill et al. 1996a). Although little detailed biochemical information is available, synergism studies (Ishaaya et al. 1987, Horowitz et al. 1988, Prabhaker et al. 1988, Dittrich et al. 1990) have implicated both mixed-function oxidases and elevated esterases in pyrethroid resistance.

### **Resistance to Synergized Pyrethroid Combinations in Southwestern United States**

Use of synergized pyrethroids was minimal before the outbreaks of sweetpotato whiteflies in the southwestern United States in the early 1990's. However, growers became more dependent on them to manage continuing problems (Ellsworth and Jones 2001, Palumbo et al. 2001). Consequently, extensive efforts were initiated to monitor susceptibility to pyrethroids in laboratory bioassays, as well as synergized combinations (Prabhaker et al. 1996, Simmons and Dennehy 1996, Dennehy et al. 1997, Sivasupramaniam et al. 1997b, Castle et al. 2001, Sivasupramaniam and Watson 2000). Despite very high densities of sweetpotato whiteflies and heavy insecticide use from 1991 to 1995, bioassay data from the Imperial Valley of California indicated that field-collected populations remained susceptible to the most commonly applied pyrethroids and synergized combinations (Castle et al. 1996a,b). Although no field control failures with synergized pyrethroids have been reported in the Imperial Valley to date, a significant shift in reduced susceptibility to fenpropathrin and acephate was detected in laboratory bioassays in 1997 and again in 1999 (Castle et al. 2001).

In Arizona, cotton and vegetable growers were experiencing similar sweetpotato whitefly outbreaks during the early 1990s. From 1993 to 1995, synergized pyrethroids, particularly the fenpropathrin+acephate combination, were essential to providing control in cotton, especially from the middle to the end of the



cotton-growing season. In 1994, evidence of reduced susceptibility to synergized pyrethroids in populations collected from cotton fields in central Arizona was documented (Dennehy et al. 1995). Monitoring of field-collected sweetpotato whitefly populations during 1995 confirmed significant reductions in susceptibility to these combinations in major cotton-growing regions (Dennehy and Williams 1997, Dennehy et al. 1997). By the end of the 1995 season, growers in some areas experienced unacceptable yield losses and sticky lint contamination following repeated use of synergized pyrethroids. Consequently, an emergency exemption (US-EPA Section 18) for buprofezin and pyriproxyfen was granted for cotton in 1996 to provide alternatives to synergized pyrethroids. Regulated use of these compounds in a conservative resistance management program for several years resulted in areawide suppression of sweetpotato whitefly populations and clearly contributed to reductions in pyrethroid use (Ellsworth et al. 1996, Ellsworth 1998, Agnew and Baker 2001, Ellsworth and Jones 2001). Presently, sweetpotato whiteflies remain relatively susceptible to synergized pyrethroids (Li et al. 2001), but results from continued monitoring of fenpropathrin and acephate suggest that a return to intensive synergized pyrethroid use could result in the rapid selection of resistant populations and control failures (Castle et al. 2001).

### **Cyclodienes**

The only organochlorine still used widely against whiteflies is endosulfan. Resistance levels in sweetpotato whiteflies to endosulfan have ranged from 20- to 360-fold in strains from many countries (Denholm et al. 1996). The resistance factors recorded, although generally lower than for OPs and pyrethroids, did reduce the performance of endosulfan under simulated field conditions (Cahill et al. 1996b). The principal mechanism of endosulfan resistance in several insects, including sweetpotato whiteflies, involves a modification of GABA-gated chloride ion channels in postsynaptic nerve membranes (Anthony et al. 1995).

### **Resistance to Novel Insecticides**

The need for a greater diversity of compounds effective against whiteflies is being met by the introduction of several insecticides with new modes of action, which are less affected by existing resistance mechanisms. Neonicotinoid insecticides—imidacloprid, acetamiprid, nitenpyram, and thiamethoxam—are generally systemic in plants and target acetylcholine receptors in the insect's central and peripheral nervous system. Insect growth regulators include inhibitors of chitin synthesis,

buprofezin and benzoylphenyl ureas such as novaluron, and the juvenile hormone mimic pyriproxyfen. Other new insecticides active against whiteflies inhibit mitochondrial ATP synthesis (diafenthiuron) or affect feeding behavior in homopteran insects (pymetrozine). Various fermentation products of *Streptomyces avermitilis*—such as abamectin (mixed with mineral oils), emamectin, and milbemectin—have been reported as effective against sweetpotato whiteflies in laboratory and field trials. These insecticides and other biorational products are generally considered to be relatively safe to natural enemies and are gradually being incorporated into whitefly control programs around the world. These compounds offer excellent prospects for regaining control of insects already resistant to the conventional insecticides. However, none should be assumed to be immune to resistance, and some cases of resistance to the novel insecticides have been reported.

### **Buprofezin**

Buprofezin inhibits chitin synthesis in several homopteran pests including whiteflies (Ishaaya et al. 1988). Its mode of action is not fully understood, although the principal effect is to interfere with chitin deposition during molting, resulting in nymphal mortality during ecdysis. In addition, the fecundity and egg hatch of females exposed to treated leaves is reduced (Ishaaya et al. 1988). Buprofezin is considered a major compound for controlling sweetpotato whiteflies in both greenhouses and outdoors, especially in locations where resistance to conventional insecticides has evolved (Horowitz et al. 1994, Dennehy and Williams 1997). Buprofezin susceptibility decreased 3 years after its introduction on Israeli cotton in 1989 (Horowitz and Ishaaya 1992, Horowitz et al. 1994). Most recently, significant decreases in susceptibility to buprofezin were detected in sweetpotato whitefly populations collected from cotton fields in the Ayalon Valley of Israel from 1992 to 1995 (Horowitz et al. 1999a). Buprofezin still provides satisfactory control in most growing areas in Israel, but its use in cotton fields in Israel is quite low.

The risk of resistance development is higher in protected crops in confined spaces, and in these habitats buprofezin resistance is now becoming widespread. Resistance levels of 10- to 50-fold have been reported from greenhouses or glasshouses in the United Kingdom, Netherlands, Spain, and Israel (Horowitz et al. 1994, Cahill et al. 1996d). Recent bioassays of

sweetpotato whiteflies collected from greenhouses in Almeria, Spain, showed that resistance to buprofezin has apparently increased since 1994 (Elbert and Nauen 2000).

Bioassays of populations collected from cotton indicated a trend of reduced susceptibility from 1996 to 1998 (Dennehy et al. 1999). Susceptibility to buprofezin increased significantly in 1999, but returned to lower levels in 2000, where a 10-fold reduction was reported in several populations (Li et al. 2001). Similarly, sweetpotato whitefly populations collected from several regions in California and Arizona in 1998 and 1999 showed an increase in susceptibility to buprofezin (Toscano et al. 2001).

### **Pyriproxyfen**

The use of pyriproxyfen during the past decade for sweetpotato whitefly control in Israel provides a striking example of how genetic and ecological factors can combine to promote resistance despite concerted efforts to prevent it. This compound exhibits juvenoid activity and inhibits hatching of whitefly eggs, directly or transovarially. Pyriproxyfen also affects nymphs by suppressing adult emergence, resulting in pupal mortality (Ishaaya and Horowitz 1992, 1995). Since 1991, it has been one of the main agents for controlling sweetpotato whiteflies in cotton fields in Israel (Horowitz et al. 1999b) and from 1996 in the southwestern United States. (Dennehy and Williams 1997).

The dynamics of pyriproxyfen resistance have been studied intensively in cotton fields and greenhouses in Israel (Horowitz et al. 1999b, 2003). Seasonal trends of susceptibility to pyriproxyfen in field populations have been monitored annually from June (prior to treatment) through late summer at different locations in Israel. Initially, only a slight decrease in susceptibility was observed during the cotton season. Because of a restriction on its use on cotton and a consequent reduction in selection pressure, pyriproxyfen could be reapplied in the following season when susceptibility has been restored. However, in a rose greenhouse after three successive applications, higher than 500-fold resistance to pyriproxyfen was recorded (Horowitz and Ishaaya 1994). After 7 years of pyriproxyfen use on cotton within a resistance management strategy that limits its use to a single application per season, susceptibility has been maintained in some areas. In other locations, such as the Ayalon Valley in central Israel, where populations of sweetpotato whiteflies are

relatively isolated geographically, moderate to high levels of resistance have been observed (Horowitz et al. 1999b).

The findings from Israeli cotton have potentially important implications for managing resistance to pyriproxyfen elsewhere. In general, a restriction to one application per season appears essential for sustaining the effectiveness of pyriproxyfen. Regions with climates and cropping systems with histories of resistance such as those of Ayalon Valley of Israel may need to implement pyriproxyfen-free years in order to effectively contain resistant genotypes.

Recent findings may implicate the existence of different biotypes of the sweetpotato whitefly as determinants of resistance development in southern Europe and the Middle East, (Horowitz et al. 2003) the two most widespread biotypes are B and Q. The B biotype has a broad geographical distribution and is considered to be a recent invader over much of its range. The Q biotype was originally considered to be restricted to the Iberian Peninsula but has recently been detected in Italy and, unexpectedly, alongside the B biotype in Israel. To date, all confirmed cases of strong resistance to pyriproxyfen in Israel have been associated with the Q rather than the B biotype (Horowitz et al. 2002). It is therefore possible that the present distribution of genes for pyriproxyfen resistance reflects the current gene flow associated with Q biotype populations.

In recent seasons (1998-2001), there has been a decline in levels of pyriproxyfen resistance in cotton fields in Israel, mostly in the western Negev (southwestern Israel) but also in the Ayalon Valley (Horowitz et al. 1999b, 2002). The decline corresponds with the cessation of pyriproxyfen use in the Ayalon Valley since 1997 and increased use of neonicotinoid insecticides, especially acetamiprid (G. Forer, 1999, personal communication). The introduction of the neonicotinoids has resulted in reduced use of pyriproxyfen, even in locations with less severe resistance to this insecticide such as the western Negev, where susceptibility to pyriproxyfen is almost restored.

In the United States, pyriproxyfen and buprofezin were first used as rotational alternatives in cotton resistance management programs beginning in Arizona in 1996 and in California in 1997. Initial monitoring of sweetpotato whiteflies collected from cotton in Arizona from 1996 to 1998 showed no reductions in susceptibility to pyriproxyfen (Dennehy et al. 1999).

However, a significant decrease in susceptibility was observed in populations collected from some Arizona cotton-growing regions in 1999 and 2000 (Li et al. 2001). Monitoring populations in southern California and southwestern Arizona revealed that regional differences in pyriproxyfen toxicity were minimal, and as with buprofezin, susceptibility to pyriproxyfen was maintained after three years of use (Toscano et al. 2001). To date, both buprofezin and pyriproxyfen remain highly effective and continue to provide economic control in California and Arizona cotton (Ellsworth and Jones 2001, Palumbo et al. 2001).

### Neonicotinoids

The use of neonicotinoid insecticides (also termed chloronicotinyl insecticides) against sucking pests is now increasing rapidly. The first commercial compound was imidacloprid. Others being introduced are acetamiprid, nitenpyram, thiamethoxam, and thiacloprid. A combination of neonicotinoid overuse, coupled with a strong risk of cross-resistance between these chemicals, threatens the effectiveness of the group as a whole (Cahill and Denholm 1999, Li et al. 2001). Although only a few cases of resistance to neonicotinoids have been reported, it is of utmost importance to develop recommended resistance management strategies for this important insecticide group (Elbert et al. 1996).

Resistance to imidacloprid has already been reported from greenhouses in southern Spain (Cahill et al. 1996c, Elbert and Nauen 2000) and in a sweetpotato whitefly strain from the United States placed under strong and prolonged selection pressure in the laboratory (Prabhaker et al. 1997). In addition, three years of acetamiprid use in Israeli greenhouses resulted in a 5- to 10-fold increase in tolerance of sweetpotato whiteflies to this compound; however, acetamiprid remained highly effective in cotton fields (Horowitz et al. 1999a).

In the Imperial Valley of California, bioassays with imidacloprid of field-collected sweetpotato whiteflies showed no evidence of resistance in 1996 (Prabhaker et al. 1997). In Arizona, where imidacloprid has been used since 1993, a slight decline in susceptibility to this compound was observed in laboratory bioassays (Dennehy et al. 1999). Subsequently, field monitoring showed that populations maintained their susceptibility to imidacloprid in 1999 and 2000 at levels similar to those reported in 1997 (Williams et al. 1998, Li et al. 2001). The inherent toxicity of systemic-applied

imidacloprid and its metabolites, and sweetpotato whitefly bionomics and diverse agro-ecosystems, may explain why efficacy of imidacloprid formulations remains relatively high in the desert cropping systems in southwestern United States (Palumbo et al. 2001).

In conclusion, sweetpotato whiteflies have the ability to develop resistance to both conventional and nonconventional insecticides. Management of this pest should be based on a rational use of insecticides, restriction of treatments, and alternation with compounds of different modes of action in order to reduce selection pressure for resistance.

### Status of Insecticidal Resistance in *Aphis gossypii*

Cotton aphids have developed resistance to pesticides worldwide, among them the major insecticide groups of the conventional insecticides such as organochlorines, OPs, carbamates (including pirimicarb), and pyrethroids (Whalon et al. 2004). Various cases of aphid resistance in cotton were reported recently in China (by Cheng et al. [1997], among others) and Australia (Herron et al. 2000, 2001). In the United States, resistance in cotton aphids has been developed to bifenthrin, chlorpyrifos, cyhalothrin, endosulfan, linden, methamidophos, methidation, methomyl, oxydemeton-methyl, phosphamidon, and sulprofos (Whalon et al. 2004). In Hawaii, resistance levels to the OP oxydemeton-methyl were more than 2,000-fold (Hollingsworth et al. 1994). Kerns and Gaylor (1992) found OP and pyrethroid resistance in cotton aphids from cotton fields in Texas and Alabama, and O'Brien et al. (1992) observed carbamates and organochlorine resistance in Mississippi cotton. So far, applications of newer insecticides (for example, imidacloprid and other neonicotinoids, pymetrozine, and diafenthiuron) have resulted in effective control of cotton aphids (Godfrey and Leser 1999, Holloway et al. 1999, Grafton-Cardwell et al. 2000, White et al. 2000, Almand and Sweeden 2001).

In the San Joaquin Valley of California the two key cotton pests are lygus bugs (*Lygus hesperus* (Knight)) and cotton aphids. Since the early 1990s, in-depth research has been conducted in the San Joaquin Valley (Grafton-Cardwell 1991, Fuson et al. 1995, Grafton-Cardwell et al. 1997, Cisneros and Godfrey 1998, Grafton-Cardwell et al. 2000) to determine the susceptibility of aphids to insecticides. Other studies evaluated the connection between early sprays against lygus bugs and development of insecticide resistance of

aphids later in the season and the effects of agronomic and environmental factors on resistance in cotton aphids. During the early 1990s, when organochlorine, OP, and carbamate insecticides exhibited reduced efficacy (Grafton-Cardwell et al. 1992) the pyrethroids were introduced, especially bifenthrin. Cotton aphids also gradually developed resistance to bifenthrin, and in 1995 high resistance levels were observed (Grafton-Cardwell and Goodell 1996). Early season bifenthrin applications against lygus bugs escalated the resistance problems.

Although cotton aphids developed resistance to insecticides in California, some interesting findings of related resistance have been reported. It was noted that OP resistance in cotton aphids is unstable and manageable through rotation of insecticides with different modes of action (Grafton-Cardwell et al. 2000); that is, resistance to chlorpyrifos increased and declined in accordance with the insecticide used. Similar resistance patterns were also observed with endosulfan and pyrethroids (Grafton-Cardwell et al. 2000).

Other studies have reported that agronomic and environmental factors are involved in insecticide efficacy against cotton aphids and may help to explain the erratic field control achieved with various insecticides (Fuson et al. 1995, Cisneros and Godfrey 1998, Godfrey and Fuson 2001). Dark aphids were less susceptible to most insecticides than light individuals, and aphids from late-planted cotton were more tolerant than those from early-planted cotton. Nitrogen supplies also affected the susceptibility of cotton aphids to insecticides. Aphid vigor, as evidenced by mean weight and fecundity, are affected by temperature and the nutritional quality of the host plant. During periods of mild, favorable temperatures, typically early in the growing season, aphids appear as dark nymphs ranging from gray to dark green and are relatively large and fertile. Later in the season, at high temperatures, aphids are pale green to yellow in appearance, lighter and less fecund than under more favorable conditions. Also, cotton leaves are generally higher in protein and sugar content earlier in the season. Consequently, the aphids tend to be more susceptible to insecticides when they are less vigorous than when they are relatively stronger.

To overcome insecticide resistance problems, insecticide resistance management guidelines encourage growers to conserve natural enemies by

avoiding broad-spectrum insecticides in the early cotton-growing season and by using pesticide rotation (for examples, see Grafton-Cardwell et al. 1997, 2000, Brazzle et al. 1998, Goodell et al. 1999). Since the implementation of such programs, resistance to OPs and organochlorine in cotton aphids has declined (Grafton-Cardwell et al. 2000).

### **Tactics of Delaying and Reducing Resistance**

Since the 1970's, various countermeasures, based largely on computer models, have been proposed for combating resistance. Most are based on manipulating operational factors defining the rate, timing, nature, and frequency of insecticide applications and on exploiting knowledge of pest biology in order to anticipate the selection pressure imposed by insecticides. As noted by several authors (including Sawicki 1981, Roush 1989, Denholm and Rowland 1992, Georghiou 1994, Castle et al. 1999), there is no single prescription for combating resistance under all situations. Tactics must be tailored as carefully as possible to individual pests or pest complexes in light of ecological and genetic factors, the diversity of chemicals available, and practical constraints on the precision with which they can be implemented.

Approaches to combating resistance can be viewed from different perspectives (such as those of Georghiou 1983, Roush 1989, Denholm and Rowland 1992, McKenzie 1996). The classification proposed by Georghiou (1983) is briefly summarized below:

- **Management by moderation** aims to reduce selection for resistance by preserving susceptible insects in the population through low application rates, less frequent applications, short-lived residues, or the creation of untreated refuges. These approaches are often the easiest to implement and involve the least risks. However, the value of lowering application rates to manage resistance remains debatable. Unless overall efficacy is compromised, there is a threat of increasing the number of resistant genes for selection (Roush 1989, Denholm and Rowland 1992, McKenzie 1996).
- **Management by saturation** aims to overpower any resistant individuals present by using doses sufficiently high to kill resistant insects (especially resistant heterozygotes), suppressing detoxification enzymes through the use of synergists, or identifying

‘resistance-defeating’ toxins less affected or unaffected by known resistance mechanisms.

- **Management by multiple attack** involves using two or more unrelated pesticides in ways that reduce the selection or the effect of resistance to any one chemical. The compounds could be applied simultaneously as mixtures, alternately in rotation, or in more complex spatial patterns known as mosaics. Although mixtures offer greater theoretical benefits than alternations, they require a far greater number of assumptions to be met regarding the efficacy, persistence, and complementarity of partner chemicals (Roush 1989, Tabashnik, 1989, Denholm et al. 1998b). All tactics in this category rely on the absence of cross-resistance between component insecticides.

In practice, strategies implemented to challenge resistance have tended to adopt combinations of the above three approaches. As an example, measures introduced in the early 1980s to combat pyrethroid resistance in the bollworm (*Helicoverpa armigera*) on cotton (Forrester et al. 1993) involved restricting the “window” duration when pyrethroids could be used (management by moderation), and recommending the use of nonpyrethroid alternatives outside this period (management by multiple attack). Other recommendations—to target pyrethroids against neonate larvae, thus enabling even pyrethroid-resistant phenotypes to be killed; and to use the synergist piperonyl butoxide with pyrethroids to suppress detoxification systems—emerged from subsequent work on the underlying mechanisms and introduced components of a management by saturation approach. Unfortunately, even these measures failed to prevent a gradual increase in the frequency of pyrethroid resistance in *H. armigera*. The Australian strategy nonetheless pioneered a number of principles relating to the design, implementation, and support of large-scale resistance management and has rightly achieved a great deal of international acclaim.

A resistance management strategy introduced in Israel in the late 1980s against sweetpotato whiteflies and co-existing cotton pests also relies heavily on restricting the use of key compounds (in this case to a single application per season) and on rotating insecticides in a sequence intended to protect beneficial organisms and to exploit nonchemical tactics as much as possible (table 1) (Horowitz et al. 1994, 1995). Again, this has not completely prevented resistance, but it has resulted

in a dramatic reduction in the number of insecticide sprays on cotton. Similar results have been obtained by extending components of the Israeli strategy to the cotton/vegetable cropping systems of the southwestern United States (table 2) (Dennehy et al. 1996, Dennehy and Williams 1997, Dennehy and Denholm 1998, Palumbo et al. 2001).

One notable feature of these and many other resistance management strategies is that they were initially formulated with little or no knowledge of the resistance mechanisms already present or likely to arise. Their primary objective was and continues to be prevention of resistant phenotypes from reaching economically damaging frequencies. In principle, this objective could be further supported by biochemical or genetic input which can serve as a base for resistance management (Horowitz and Denholm 2001).

## Discussion

Insecticide resistance in sweetpotato whiteflies and cotton aphids is widespread in the United States and elsewhere. At present, it seems that resistance problems are more severe and far-reaching for sweetpotato whiteflies than for cotton aphids, but field failures of insecticides and lint stickiness difficulties for both pests have been reported. The new groups of insecticides of most interest are the insect growth regulators buprofezin and pyriproxyfen, which have already been proved to be prone to resistance in sweetpotato whiteflies, and the neonicotinoids, whose forerunner, imidacloprid, is now in widespread use against whiteflies and other pests including aphids. Although neonicotinoid insecticides have given outstanding operational versatility, their vulnerability to cross-resistance requires that resistance management tactics be directed at the group as a whole rather than at single compounds (Elbert et al. 1996, Cahill and Denholm 1999).

Insecticide resistance management strategies implemented in Israel and the United States for combating resistance against sweetpotato whiteflies and cotton aphids—based on optimal but restricted use of new insecticides, structured resistance monitoring, and the exploitation of other management tactics such as natural enemies—currently provide the best available model for combating resistance in these pests.

**Table 1. Insecticide resistance management programs in cotton in Israel (after Horowitz et al., 1999a)**

[Key pests are whiteflies (*Bemisia tabaci*) and pink bollworms (*Pectinophora gossypiella*)]

	Period & month			
	I	II	III	IV
	mid April to mid May	mid May to mid July	mid July to mid Aug.	mid Aug. to mid Sept.
Pests	<i>Aphis gossypii</i>	<i>Helicoverpa armigera</i> <i>P. gossypiella</i>	<i>B. tabaci</i> <i>P. gossypiella</i> <i>Earias insulana</i>	<i>B. tabaci</i> <i>P. gossypiella</i> <i>E. insulana</i> <i>Spodoptera littoralis</i>
Pesticides	N/A	N/A Endosulfan <sup>2</sup> Pheromone ropes <sup>2</sup>	Pyriproxyfen <sup>1</sup> Neonicotinoids <sup>1</sup> Pyrethroids OPs <sup>4</sup> Carbamates	Buprofezin <sup>1</sup> Diafenthiuron <sup>1</sup> BPUs <sup>3</sup> OPs

<sup>1</sup> For controlling *B. tabaci*.

<sup>2</sup> For disrupting mating of *P. gossypiella*

<sup>3</sup> BPU (benzoylphenyl urea): for controlling *S. littoralis*.

<sup>4</sup> OP: organophosphate insecticides

**Table 2. Insecticide resistance management strategies for silverleaf whiteflies on cotton in Arizona and in San Joaquin Valley, California**

Stage <sup>1</sup>	Insecticides	
	Type	Brand names
Initial buildup	IGRs:	Bruprofezin <sup>3</sup> Pyriproxyfen <sup>3</sup>
Gradual invasion	Nonpyrethroids:	Imidacloprid Endosulfan Amitraz
Heavy migration <sup>2</sup>	Pyrethroid mixtures	Endosulfan <sup>4</sup> bifenthrin <sup>4</sup> Pyrethroid + Endosulfan <sup>4</sup> Fenpropathrin + Acephate/Profenofos

Source: Ellsworth et al. 1996, Brazzle et al. 1998

<sup>1</sup> Three-stage chemical use for cotton as part of whitefly management strategies:

Stage I: Insect growth regulators. Use IGR of choice when whitefly counts exceed threshold.

Stage II: Nonpyrethroids. When populations average more than five adults per leaf.

Stage III: Pyrethroid mixtures. Delay pyrethroid use until the end of the control season.

<sup>2</sup> Late-season heavy migrations.

<sup>3</sup> Both materials act mainly on the immature stages; therefore, eggs and nymphs should be present prior to treatment. Use only one application of each IGR per season.

<sup>4</sup> According to California guidelines.

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## Chapter 10

### Approaches to Microbial and Enzymatic Remediation of Sticky Cotton

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Although effective programs for management of sweetpotato whiteflies and cotton aphids are available, in some instances, because of insufficient attention by producers or inadequate insect control, cotton lint may become contaminated by insect honeydew. High concentrations of honeydew contamination in regions with high humidity are typically visible as sooty molds, (*Aspergillus* and *Penicillium* spp.). However in arid regions, where sweetpotato whiteflies are often found, seed cotton can be quite sticky without the condition being obvious to the observer. Thus the first impediment to remediation may be detection. If cotton is determined to be contaminated with honeydew before it is picked, there are possibilities for remediative action by overspraying with microbials or enzymes before picking and treating at picking, when moduling, when ginning, and possibly when compressing. If the chemical requirements for honeydew decomposition are known, appropriate chemical or biochemical remediation may be attempted if there are means to direct the remediative product to the target and if the appropriate conditions for successful reaction can be accomplished without creating disadvantage side-reactions.

#### Microbes on Cotton Fibers

A wide variety of microorganisms are found on cotton plants and cotton fiber (Simpson and Marsh 1971, Klich 1986, Hillocks and Brettell 1993, Chun and Perkins 1996a,b, Elliott 2002). Some of them readily metabolize honeydew sugars, especially in the presence of amounts of moisture that support microbial growth (Wyatt and Heintz 1982, Couilloud 1986, Hillocks and Brettell 1993). The range of conditions that permit microbial growth on cotton fiber are unknown.

Researchers have tried adding various microorganisms to honeydew-contaminated lint to reduce stickiness (Elsner 1980, Bailey et al. 1982, Blasubramanya et

al. 1985). Other approaches have been to encourage microbial growth by supplementing honeydew-contaminated lint with nutrients (Heur and Plaut 1985). A potential problem with these methods is that several genera of fungi found on cotton are capable of discoloring and weakening lint fibers (Marsh et al. 1950). Loss of fiber strength can lead to breakage during spinning, and the value of lint can be lost due to discoloration. In addition, some of the gram-negative bacteria that live on cotton fibers can produce endotoxins that can cause serious decreases in pulmonary function in textile workers (Neal et al. 1942, Castellan et al. 1984, 1987, Rylander et al. 1985). Therefore, creating conditions that accelerate the growth of microbes to degrade honeydew on lint risks undesirable growth of gram-negative bacteria that are a human health hazard.

Recent studies have identified more than 250 yeasts that are capable of degrading honeydew sugars (Elliott 2002). Some of these may not have significant adverse effects on cotton quality or be a human health risk. Additional study may be warranted to determine their potential as a possible solution to the sticky cotton problem.

#### Enzymatic Degradation of Honeydew

Another approach to reduce stickiness in cotton is the use of enzymes to hydrolyze honeydew sugars on contaminated lint. Hendrix and Wei (1992) reported that sprays of aqueous solutions of Tempanil, which contains glucose oxidase, significantly reduced sugars of sweetpotato whitefly honeydew on cotton lint in laboratory experiments. Also, Hendrix et al. (1993) found that an experimental proprietary product called "Enzyme A" applied to sticky cotton lint significantly reduced stickiness measured by the minicard test. Based on the chemistry of the major sugars in sweetpotato whitefly honeydew (Hendrix et al. 1992, Hendrix and Wei 1994, Wei et al. 1996, 1997), another proprietary enzyme product, Transglucosidase L-500, was suggested to have greater potential for honeydew hydrolytic activity than the product previously offered (Lantero and Shetty 1996). To see if the later enzyme could be effectively applied prior to harvest, Transglucosidase L-500 was applied to defoliated cotton on plants in the field with conventional spray equipment. Cotton lint stickiness in the field tests was not reduced (Chu et al. 1996), most likely because most of the spray did not hit the open bolls and the moisture

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content of the seed cotton (3.5 to 5.1 percent) was well below the threshold for enzyme activation.

Since insect honeydew comprises a mixture of carbohydrates, the precise chemistry involved in degradation of sugars causing lint stickiness by these two enzymes remains undescribed in detail. However, Hendrix et al. (1993), reported that Enzyme A dramatically reduced cotton stickiness without completely eliminating extractable sugars from the treated seed cotton. The authors also found that Enzyme A hydrolyzed sweetpotato whitefly honeydew oligosaccharides—sucrose, melezitose, and trehalulose—into their monosaccharide components, glucose and fructose. Transglucosidase L-500 also hydrolyzed the same oligosaccharides to monosaccharides (Lantero and Shetty 1996), but more effectively than Enzyme A. The fate of these increased amounts of reducing sugars is unknown, but it seems likely that microflora on the fiber would metabolize the glucose and fructose produced into carbon dioxide and water.

Nearly all of the oligosaccharides in insect honeydews are nonreducing sugars, but decomposition experiments show that they consist of monomers that are approximately 90 percent glucose and 10 percent fructose (chapter 4). Hendrix (1999) therefore concluded that if a large percentage of the nonreducing sugars produced by whiteflies were degraded to monosaccharides by these enzymes, the result would be an increase in glucose and fructose content in the lint. In experiments in which honeydew and other sugars were artificially applied to clean lint, Miller et al. (1994) found that, although glucose and fructose made cotton sticky, lint sprayed with these sugars was less sticky than that sprayed with the equivalent amount of honeydew oligosaccharides. A significant, but temporary, increase in thermodetector (SCT, described in chapter 13) counts was usually observed after enzyme treatment of contaminated lint. Such an increase in SCT counts might at least partly be caused by the increased lint monosaccharide content created by breakdown of carbohydrates of higher molecular weight.

Laboratory studies with seed cotton moisture contents of 5, 10, 15, 20, and 25 percent by weight with or without Transglucosidase L-500 resulted in reduced lint stickiness counts as moisture content increased (Henneberry et al. 1997). The moisture content of the untreated seed cotton was 4.5 percent and SCT counts

averaged 26.3 (table 1, experiment 1). Five days of incubation after treatment showed an average SCT count of 30.3 for the water-sprayed samples at 8.6 percent seed cotton moisture. SCT counts decreased with each increasing level of seed cotton moisture. SCT counts for all samples at 14.3 percent and greater seed cotton moisture percentages were lower than that of untreated seed cotton. SCT counts for samples with 8.6 and 13.9 percent seed cotton moisture were not statistically different from controls. Solutions of 1 percent Transglucosidase L-500 in water at an average moisture level of 11.3 to 19.7 percent (table 1, experiment 2) reduced SCT counts during a 5-day incubation period.

In the field, water (table 2) or a water plus Transglucosidase solution (table 3) was applied to honeydew-contaminated lint during harvest with a spray boom mounted in front of a spindle picker and in the seed cotton ducts leading to the picker basket (Henneberry et al. 1997). The treatments did not effectively reduce cotton lint stickiness (tables 2 and 3). But when seed cotton moisture content ranged from 9.0 to 15.0 percent and higher (table 3), SCT counts were significantly less for duct-treated seed cotton than for untreated seed cotton measured on the day of treatment and 7 and 14 days following treatment, but only on day 7 following treatment for the boom treated cotton. The data suggested that treatment of seed cotton with water plus Transglucosidase L-500 solution that resulted in 9 percent or higher seed-cotton moisture induced a more rapid reduction in cotton stickiness counts than treatments with water alone at similar seed cotton moisture content.

Moisture levels that are too high in moduled cotton cause detrimental effects due to excessive microbial growth (Sorenson and Wilkes 1972, Curley et al. 1988), and moisture that is too low will not allow enzyme activity at effective rates. The use of enzymes to reduce stickiness of honeydew-contaminated cotton thus is constrained by a requirement for a precise application of moisture. For success, enzyme solutions with less than 12 percent moisture must be employed. At such moisture contents incubation periods of weeks to a few months may be required to compensate for the relatively small amount of water added during seed-cotton spraying. One possibility that has been considered to accomplish this objective was to apply the enzyme to cotton as it is delivered and formed into modules. It was postulated that the treated cotton could then be held for several weeks in the field prior to



ginning, during which time the cotton stickiness in the modules could be monitored. An experiment to test this hypothesis was carried out in which seed cotton was sprayed with water alone or water-enzyme solutions and packed into simulated cotton modules consisting of 1.8 m<sup>3</sup> plastic-lined plywood boxes (Hendrix et al. 2001). Unsprayed seed cotton packed in similar simulated modules served as control.

Treatments were a factorial arrangement of Transglucosidase L-500 at 0, 295, and 824 enzyme units per kilogram of seed cotton at 8, 10, and 12 percent seed-cotton moisture. As the seed cotton was packed into the boxes, it was sprayed with carbohydrate-degrading enzyme in water at rates of between 0.08 and 0.26 L/kg. After spraying, the cotton in the boxes was compressed to a density of 146 to 216 kg/m<sup>3</sup>. The thermal dynamics and stickiness of the seed cotton in the simulated modules, and the length, strength, and color of the cotton fiber were measured during a 6-week storage period. Sprays containing medium or high enzyme rates and 8 percent lint moisture content did reduce the stickiness and extractable sugar content of the fiber, but at higher rates of enzyme application the moduled cotton became discolored after extended module storage.

Over the storage period in the simulated modules (table 4), the moisture content of those sprayed to a target moisture of 8 percent decreased, on average, by 1.25 percent. The average seed cotton moisture content in those boxes sprayed to a target moisture of 10 percent decreased 1.45 percent, and those sprayed to a 12 percent target moisture decreased 1.89 percent.

Temperatures in the simulated modules with no added water closely tracked the average ambient temperature (figure 1). The water treatments of 0.060 and 0.087 liters per kilogram of seed cotton did not cause significant heating of the simulated modules. In the modules to which 0.132 or 0.146 L/kg water was added, moderate heating above ambient temperature was observed and persisted for about 3 weeks; with water added in amounts of 0.187 and 0.231 L/kg, temperature increased as much as 17 °C and the increased temperatures persisted throughout the storage period. The elevated temperatures suggest increased microbial metabolism. We hypothesize that such microbial activity would result from both the increase in moisture and the accelerated microbial activity. The monosaccharides released into the moist

lint would cause the native microflora to multiply rapidly.

Even though the values of stickiness determined by SCT exhibited considerable variation, a significant decrease in stickiness could be discerned with increasing rates of water application (table 5), especially at longer storage periods. The effects of enzyme application rate on stickiness were less evident than the relationship between stickiness and water application rate. However, for those samples with an 8 percent moisture content, a consistent decrease in stickiness was observed with increasing enzyme application.

The amount of trehalulose and melezitose sugars on lint significantly decreased with increasing module lint water content (table 6), and the pattern of this increase is in general agreement with the stickiness reduction determined by the thermodetector (table 5). This decrease in trehalulose and melezitose content was especially evident over longer storage periods.

Microbes living on cotton fiber might explain much of the decrease in stickiness observed in modules with the highest fiber water contents. If microbial growth becomes very rapid it can lead to module heating (figure 1; also see Curley et al. 1988, Roberts et al. 1996, Sorenson and Wilkes 1972). Note that seed cotton modules that were intended to be brought up to a 12 percent moisture content actually contained between 13.9 to 15.8 percent water (table 7).

Color ratings were not substantially decreased in seed cotton which was sprayed to 12 percent or less water (table 7). However, cotton in those boxes having a water content between 13.9 and 15.8 percent and stored for 35 or more days did suffer a significant loss in color grade. This loss of color grade was primarily due to an increase in fiber yellowness (USDA 1956).

## Summary of Enzyme Remediation Research

The use of enzymes that specifically eliminate stickiness of honeydew-contaminated lint might be a way to solve the sticky cotton problem. In a fairly dry environment, carbohydrate-degrading enzymes would require a substantial amount of time for action; thus, treating modules with enzymes is a possibility. The most promising enzymes for this purpose are carbohydrate hydrolases. The results of this minimodule trial showed that adding moderate amounts

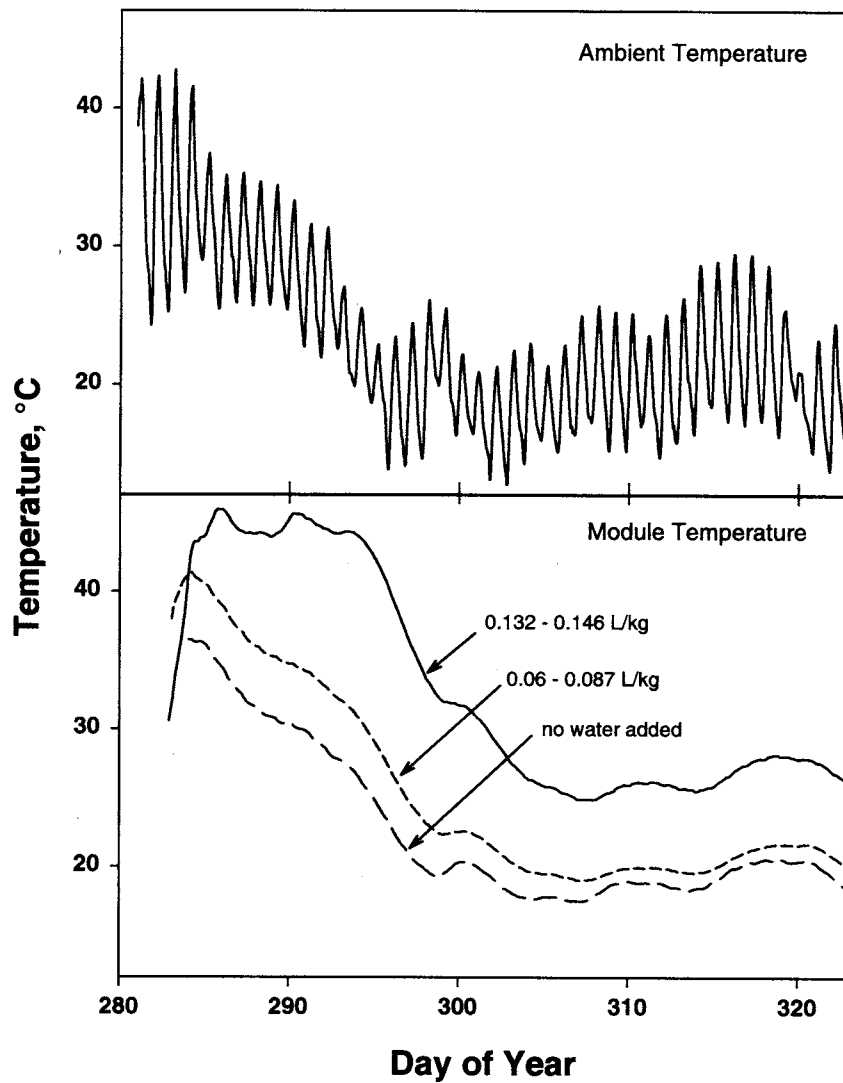


Figure 1. (Top panel) Hourly ambient air temperature recorded with thermocouples placed outside the 1.8-m<sup>3</sup> boxes. (Bottom panel) Representative graphs of seed cotton temperatures within modules which were either not sprayed (no water added), contained on intermediate enzyme solution content (0.06-0.87 L/kg), or contained the highest enzyme solution content (0.132-0.146 L/kg). The temperatures measured in modules which had the lowest water content were superimposable on the “no water added” treatment and are therefore not shown.

of water, and in some instances enzyme, to honeydew-contaminated seed cotton reduced its stickiness and did not significantly reduce cotton quality. Enzyme treatment appeared to have a more substantial effect on cotton lint trehalulose and melezitose content than on stickiness readings measured by the thermodetector. The enzyme treatment of honeydew-contaminated cotton fiber thus holds potential for the reduction of fiber stickiness, but this procedure needs further work to be considered commercially viable.

Between 1993 and 1997, a concerted research effort was undertaken by USDA-ARS, Cotton Incorporated, the University of Arizona, and commercial cooperators, prominently including Solvay Enzymes (later Genencor) to develop a method of using enzymes to reduce stickiness. The enzymatic requirements for decomposition of the several honeydew sugars were identified, and the decomposition of mixtures of honeydew sugars and honeydew on contaminated lint was accomplished on a laboratory scale. Experiments

attempted to apply enzyme products that had been successfully employed in the laboratory to cotton on plants before they were picked, to seed cotton in the picker, and to seed cotton as it was packed in the module. While there was some success, overall a successful scale-up was not achieved. One problem was that the moisture levels required for effective activity of the tested transglucosidases were near the upper bound for permissible moisture content in cotton modules, 12 percent. Thus, the basic problem was delivering the enzyme product to the honeydew deposits in a sufficiently thorough manner while not introducing more moisture than could be tolerated without generating biological heating, cotton spoilage, or lint discoloration.

Enzymatic remediation of seed cotton does not appear to be limited by lack of biologically active products, but by economical application technology and the moisture required for effective enzyme activity.

**Table 1. Effects of seed cotton moisture and Enzyme B<sup>a</sup> treatment on cotton lint stickiness: Laboratory experiments 1-3**

[Means of 5 replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Treatment and estimated seed cotton moisture	Actual seed cotton moisture	Thermodetector count
	%	
<u>Experiment 1 (5-day incubation period)</u>		
Untreated (no water)	4.5 d	26.3 ab
Water alone		
5	8.6 c	30.3 a
10	13.9 b	16.5 bc
15	14.3 b	6.0 cd
20	17.2 a	3.5 d
25	19.9 a	3.3 d
<u>Experiment 2 (5-day incubation period)</u>		
Untreated (no water)	5.2 f	26.5 a
Water plus 1% enzyme		
5	8.4 c	29.5 a
10	11.3 d	7.5 b
15	14.7 c	3.8 b
20	17.8 b	4.3 b
25	19.7 ab	5.0 b
<u>Experiment 3 (1-day incubation period)</u>		
Untreated (no water)	4.9 c	29.8 a
Water alone		
8	8.2 b	27.3 ab
10	9.3 b	23.3 a-c
12	12.1 a	15.0 cd
Water plus 1% enzyme		
8	8.4 b	19.5 bc
10	8.5 b	18.8 bc
12	9.1 b	9.0 d

Modified from Henneberry et al. 1997

<sup>a</sup> Proprietary product of Genencor.

**Table 2. Effects of applying water and water plus 1% enzyme B<sup>a</sup> at cotton picker intake duct and spray boom on seed cotton moisture and thermodetector counts: Field experiment 1**

[Means of 4 replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Incubation period and application method	Thermodetector count		Seed cotton moisture	
	Duct	Boom	Duct	Boom
gal/acre			.....%	.....
2 days <sup>2</sup>				
60	14.5 a	16.8 a	9.1 a	10.6 a
40	26.5 a	7.5 a	7.5 a	10.3 a
20	29.5 a	15.8 a	6.7 a	9.9 a
7 days <sup>2</sup>				
60	35.8 a	24.0 a	11.4 a	11.7 a
40	38.8 a	20.2 a	7.7 a	13.1 a
20	35.0 a	38.5 a	6.2 a	9.2 a
<b>Means</b>				
Boom vs. duct	30.0 A	20.5 B	8.1 B	10.8 A
Mean incubation (days)				
2	23.5 B	13.3 C	7.7 B	10.2 A
7	36.5 A	27.6 AB	8.4 B	11.4 A

Modified from Henneberry et al. 1997

<sup>a</sup> Proprietary product of Genencor.

**Table 3. Thermodetector (SCT) counts and seed cotton moisture (SCM) for machine-picked cotton untreated or treated with water plus 1 % Enzyme B<sup>a</sup>: Field experiments 2-5**

[Means of 4 replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Incubation period and post-treatment	Experiment									
	2		3		4		5			
	TD	SCM	TD	SCM	TD	SCM	TD	SCM	TD	SCM
1 day	%									
Untreated	21.0 ab	8.2 a	13.3 a	10.5 c	24.5 bc	8.2 a	21.5 a	9.5 b		
Enzyme <sup>1</sup>										
Boom	29.8 a	8.0 a	12.3 ab	10.8 a	–	–	15.0 b	9.3 b		
Duct	13.5 b	10.1 a	4.8 c	11.6 a	–	–	4.0 cd	15.0 a		
7 days	%									
Enzyme <sup>1</sup>										
Boom	14.0 b	9.5 a	6.8 bc	10.9 a	18.5 bc	8.4 a	26.0 a	10.7 b		
Duct	16.5 b	10.2 a	6.3 bc	11.0 a	13.3 c	9.4 a	5.3 cd	14.8 a		
14 days	%									
Enzyme <sup>1</sup>										
Boom	23.0 ab	8.1 a	16.0 a	9.0 a	29.8 b	9.2 a	8.0 c	10.9 b		
Duct	20.8 ab	0.5 a	5.3 c	11.9 a	15.3 c	10.0 a	1.3 d	15.0 a		
28 days	%									
Enzyme <sup>1</sup>										
Boom	18.0 b	8.6 a	–	–	48.5	–	–	–		
Duct	12.5 b	10.1 a	–	–	17.0 c	–	–	–		

Modified from Henneberry et al. 1997

<sup>a</sup> Proprietary product of Genencor.

**Table 4. Seed cotton moisture treatment, density, and enzyme applied per kg of seed cotton**

[Means of two or three replicates. Results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Treatment		Cotton moisture <sup>a</sup>							
Enzyme concentration	Seed-cotton density	Water added <sup>b</sup>	Before treatment	Days after treatment					
				0	7	14	21	28	35
		kg/m <sup>3</sup>							
		L/kg*							
Check									
0	146	0.0001	4.82 cd	4.95 f	5.19 g	4.80 f	4.92 f	5.20 d	5.00 e
Low moisture									
0	172	0.079	4.84 d	7.81 e	6.98 f	6.77 e	6.78 e	6.73 c	6.80 d
236	182	0.073	5.35 bc	8.64 de	8.18 e	7.75 d	7.66 d	7.37 c	7.72 d
813	157	0.085	6.20 a	8.95 d	8.07 e	7.82 d	7.52 de	7.89 c	7.17 d
Intermediate moisture									
0	191	0.144	5.02 bd	11.78 c	11.17 d	11.03 c	10.59 c	10.89 b	10.24 c
242	185	0.150	5.17 bd	12.22 c	11.50 d	11.04 c	10.22 c	10.24 b	9.72 c
734	193	0.165	5.43 bc	12.06 c	11.61 d	11.24 c	10.66 c	10.58 b	10.66 bc
High moisture									
0	198	0.260	4.63 d	13.95 b	13.13 c	12.58 b	12.55 b	12.60 a	11.88 ab
224	210	0.212	5.52 ac	15.62 a	13.89 b	13.61 a	13.35 ab	13.33 a	13.23 a
606	216	0.191	5.72 ab	15.83 a	14.50 a	13.60 a	13.56 a	13.81 a	13.81 a

<sup>a</sup> Factorial analysis; no significant seed cotton moisture, enzyme interactions.

<sup>b</sup> From water meter measurements.

\* kg of seed cotton.

**Table 5. Seed cotton thermodetector counts on the day of and at 7-day intervals after application of water alone or water plus different amounts of enzyme**

[Means of two or three replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Treatment	Days after treatment <sup>a</sup>						
	0	7	14	21	28	35	42
units/kg*							
Check							
0	27.1 a	22.6 ab	37.3 ab	23.4 a	22.8 a	32.4 a	19.2 a
Low moisture							
0	25.1 ab	20.8 ab	38.6 a	20.8 a	23.5 a	35.7 a	19.5 a
236	13.4 d	11.1 cd	20.8 c	5.1 bc	12.7 cd	15.4 bc	14.8 a
813	16.3 bd	19.6 ac	24.7 bc	8.9 b	18.7 ab	19.1 b	12.6 a
Intermediate moisture							
0	18.5 ad	19.3 ac	21.7 cd	20.3 a	14.1 bc	17.2 bc	12.2 b
242	22.7 ac	21.0 ab	17.8 cd	18.3 a	17.2 bc	17.4 b	13.8 b
734	20.6 ad	24.5 a	11.8 cd	23.9 a	16.9 bc	16.3 b	11.2 b
High moisture							
0	21.2 ad	10.5 d	14.7 cd	4.6 bc	8.8 de	9.2 cd	5.7 c
224	19.9 ad	15.8 bd	10.6 d	0.0 c	5.8 e	6.8 d	4.3 c
606	14.6 cd	14.4 bd	13.3 cd	10.3 b	5.6 e	8.2 d	5.3 c

<sup>a</sup> Factorial statistical analyses with days as treatments. Significant factorial interactions occurred with days at different levels of moisture, days at different amounts of enzyme, and moisture at different levels of enzyme.

\* kg of seed cotton.



**Table 6. Mean amount of trehalulose and melezitose on cotton lint following enzyme treatment.**

[Means of two or three replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Enzyme treatment	Days after treatment					
	0		35		42	
	Trehalulose	Melezitose	Trehalulose	Melezitose	Trehalulose	Melezitose
units/kg*	-----g/kg*-----					
Check						
0	2.46 a	1.64 a	3.26 a	1.84 ab	2.69 a	1.68 ab
Low moisture						
0	2.86 a	1.83 a	3.13 a	2.01 a	2.66 ab	1.87 a
236	0.99 a	0.65 a	1.25 bc	0.73 ef	1.22 de	0.82 df
813	1.14 a	0.74 a	1.18 b	1.04 de	1.78 cd	1.09 c-e
Intermediate moisture						
0	2.43 a	1.28 a	2.81 a	1.55 bc	1.93 ac	1.10 ce
242	2.72 a	1.52 a	2.54 a	1.57 bc	2.21 ac	1.49 ac
734	2.44 a	1.57 a	1.86 b	1.33 cd	1.65 bd	1.19 bd
High moisture						
0	2.30 a	1.23 a	0.72 cd	0.83 ef	0.77 de	0.84 df
224	2.13 a	1.31 a	0.33 d	0.45 f	0.60 e	0.59 ef
606	2.08 a	1.15 a	0.41 d	0.46 f	0.26 e	0.38 f

\* kg of seed cotton.

**Table 7. Enzyme- or water-treated cotton quality measurements on day of and 35 days following spraying**

[All values represent means of two or three replicates; results in a column not followed by the same letter are significantly different at  $P \leq 0.05$  by the method of least significant differences]

Moisture	Enzyme	Micronaire	Hunter's yellowness (+b) <sup>a</sup>	Reflectance (Rd) <sup>a</sup>	Color grade <sup>a</sup>	Elongation (EI) <sup>a</sup>
%	units/kg*					
Check						
4.85 <sup>b</sup>	0	4.7 b	8.5 b-d	68.0	Low middling white	9.42 a
4.95 <sup>c</sup>	0	4.6 bc	8.2 cd	68.9	Low middling white	9.41 b
Low moisture						
7.81	0	4.6 bc	8.4 b-d	69.7	Strict low middling white	9.53 b
8.64	236	4.9 a	8.3 cd	72.7	Strict low middling white	9.78 a
8.95	813	4.8 ab	7.6 d	70.2	Strict low middling white	9.60 ab
Intermediate moisture						
11.78	0	4.5 cd	8.4 b-d	69.3	Strict low middling white	9.01 dc
12.22	242	4.7 b	9.4 ab	69.1	Strict low middling white	9.18 c
12.06	734	4.7 b	8.7 bc	70.6	Strict low middling white	9.08 cd
High moisture						
13.95	0	4.7 b	9.4 ab	64.9	Low middling light spotted	8.98 de
15.62	224	4.6 bc	9.9 a	66.2	Strict low middling spotted	8.83 ef
15.83	606	4.4 d	9.9 a	64.6	Low middling spotted	8.70 f

<sup>a</sup> For descriptions of these classification factors, see USDA 1956.

<sup>b</sup> Prior to incubation.

<sup>c</sup> After 35 days of incubation.

\* kg of seed cotton.

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## Chapter 11

### Harvesting and Ginning Sticky Cotton

*S.E. Hughs*

In the United States, honeydew-contaminated cotton causes problems mainly during manufacturing and processing of yarn. The honeydew causes fibers to stick to the equipment during carding, drawing, roving, and spinning (Perkins 1987). Documentation of processing problems caused by cotton stickiness from insect honeydew in textile mills goes back as far as 1942 (Perkins 1991). Until the 1970s, the problem was mostly confined to textile mills that were processing cottons from some African countries. In 1977, certain San Joaquin Valley cottons caused problems for textile mills processing U.S. cottons (Perkins 1983). Initially the stickiness was attributed to insects but was later blamed on natural plant sugars because of its uniform rather than spotty distribution on the cotton fibers (Hughs et al. 1994b). Significant problems with U.S. cottons being sticky were not reported again until 1986 (Perkins and Bassett 1988). Again the sticky problems were encountered with San Joaquin Valley cottons, but this time the source of the stickiness was attributed to honeydew from a late-season cotton aphid infestation.

Stickiness did not recur to any great extent between 1988 and 1990 but was a very serious problem again during the 1991 and 1992 growing seasons (Hughs et al. 1994b). Before the 1991 season, processing problems with sticky cottons were not detectable until the cotton reached the textile mill. However, the 1991 and 1992 stickiness problems were so severe that difficulties were encountered even in ginning. This time the cotton stickiness came primarily from sweetpotato whitefly honeydew and occurred primarily in Arizona and over a wide section of that state's growing area.

Before the 1991 crop, the Southwestern Cotton Ginning Research Laboratory had done preliminary research on the efficacy of applying commercial textile additives during the ginning process (Hughs et al. 1993). The sticky cotton used for this 1990 test did not cause any problems during ginning, but the cotton had been previously evaluated by the minicard test as being too sticky to be processed unaided through the textile mill (Brushwood and Perkins 1993). These preliminary tests showed that the addition of commercial textile additives (fiber lubricants) to cotton during the ginning process could improve textile mill processing. Because

of the increase in the severity of the sticky cotton problem in Arizona in the 1991 and 1992 growing seasons (which affected both ginning and textile processing), the ginning research was expanded to include developing methods of dealing with cotton that was sticky enough to affect the ginning process.

### Ginning Methods and Problems

The ginning problems in 1991 and 1992 were confined primarily to the central cotton-growing region of Arizona, but involved thousands of bales. Severe difficulties in both saw- and roller-ginning plants greatly decreased hourly ginning rates and in some cases brought production to a complete standstill. There was anecdotal evidence of modules of sticky seed cotton reducing 30 bale/hour gin plants to 10 bales per 12-hour shift. Ginning problems had the same general characteristics as those in the textile mill—honeydew residue from contaminated seed cotton would build up, causing cotton fiber to adhere to various metal and other working surfaces. Gradually the fiber buildup would cause processing slowdowns and finally completely stop the ginning process. Once this happened, the affected surfaces would have to be washed with soap and water to remove the honeydew contamination and accumulated cotton fiber residue. Then the honeydew buildup would start all over again once ginning production had resumed.

Roller-gin plants are much more vulnerable to slowdowns and stoppages due to honeydew buildup than are saw-gin plants. Their vulnerability is due to the design of the roller-gin stand itself (figure 1). A roller gin stand removes fiber from the seed by pulling the cotton fiber underneath a stationary metal “knife” that is pressed against the rotating roll. This roll is covered with a material, known as roll packing, that is composed of a cotton duck material laminated in layers with rubber. The friction of the moving packing material on the cotton fiber pulls the fiber underneath the stationary knife and off the seed. The frictional properties of the roll pulling on the cotton fiber as well as those of both fiber and roll sliding against the stationary knife are important to the proper operation of a roller-gin stand.

The contact pressure of the metal stationary knife running against the roller-gin stand roll and the resulting frictional heat cause the honeydew to accumulate on the knife surface that contacts the roll as well as on the roll itself. The rate of accumulation

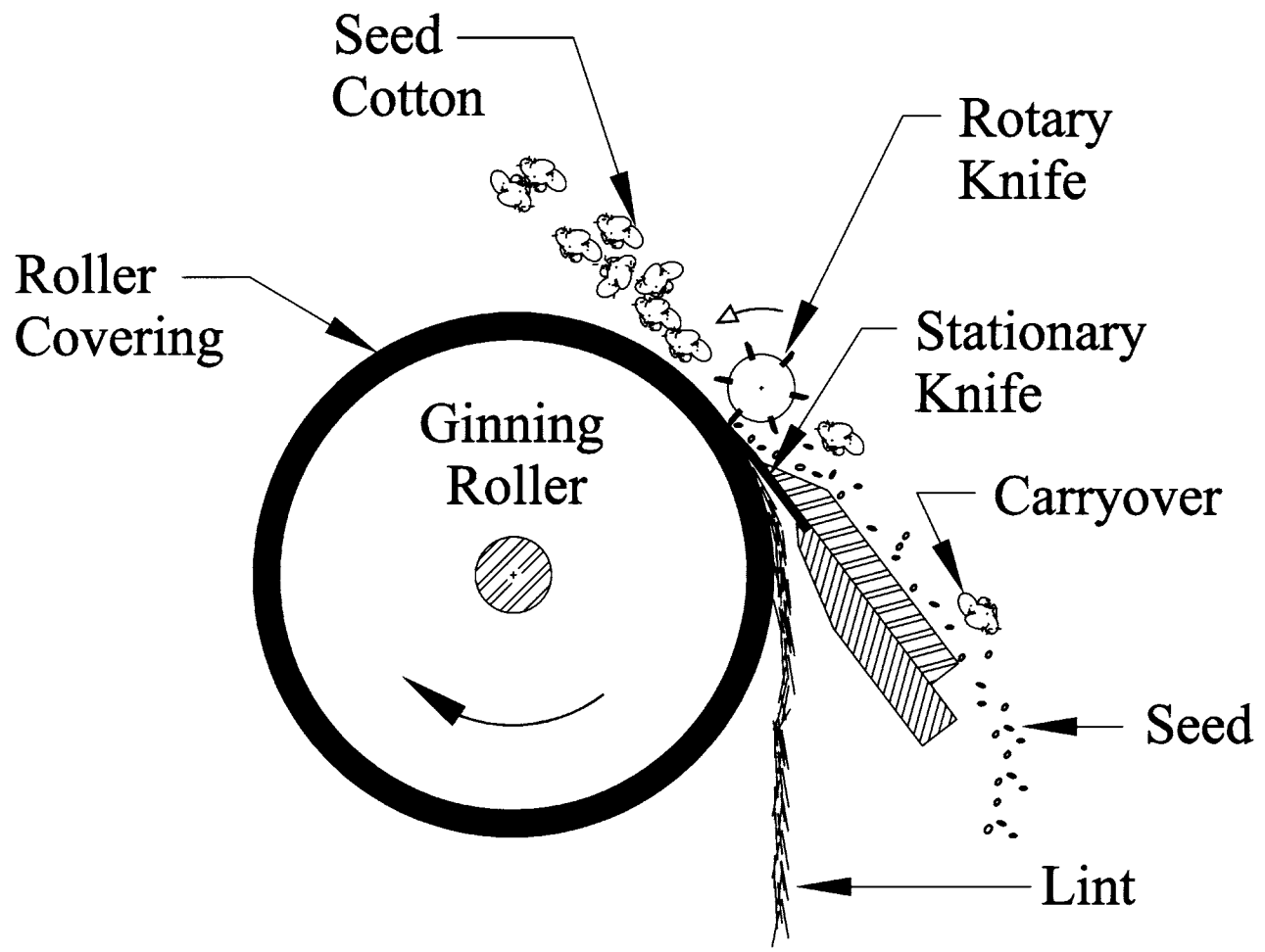


Figure 1. Rotary knife roller gin.

is very dependent on the amount of honeydew present in the raw seed cotton. Any honeydew on the active surface of the stationary knife decreases ginning rate, but ginning ceases completely when the metal surface is completely covered with honeydew. Likewise, honeydew accumulating on the roll surface alters the frictional properties of the gin roll and also decreases ginning rate. One readily observable symptom of a decreasing roller-ginning rate is a steadily increasing amount of seed-cotton carryover at the gin stand for a given feed rate. Seed-cotton carryover is unginning seed cotton that is fed to the roller gin stand but is not picked up by the ginning roll and stationary knife. This unginning seed cotton “carries over” with the ginned seed, is reclaimed from the seed line, and circulated back through to the seed cotton flow to the gin stand. When the active metal surface of the stationary knife gets completely coated with honeydew, all of the seed cotton fed to the stand goes to carryover and ginning ceases. At this point the affected roller-gin stand is shut down, and the contaminated surfaces must be cleaned of honeydew residue.

Cleaning honeydew residue from the stationary-knife and roll is difficult. When the roll is pulled back from the stationary knife to inactivate the gin stand, there is only about one-quarter to one-half inch clearance between the knife and the roll surface. Also, the roll cannot be washed with soap and water since a wet ginning roll is unusable until it can be dried out again, a time-consuming process. About the only recourse is to use a thin blade or file inserted between the stationary knife and the roll to mechanically scrape the honeydew from the knife. Sometimes sandpaper is used to scrape the surface of the roll to remove some of the accumulated honeydew. If there is no further contamination, this procedure will partially restore the ability of the roller-gin stand to function, and the stand will eventually return to full capacity as the honeydew gradually wears off the ginning roll. If there is continual contamination, this procedure will be repeated often, causing great loss in productivity. Roller-gin plants normally consist of 12 or more individual roller-gin stands. Having to continually remove accumulated honeydew from each gin stand is a very labor-intensive, expensive, and time-consuming process.

Saw-gin stands are much less susceptible than roller-gin stands to production stoppages from honeydew contamination because of their design. Ginning action in a saw-gin stand does not rely on friction but on

the mechanical pulling of fiber by saw teeth through two closely spaced ribs (figure 2). Honeydew can and does build up in this area, but it requires a much greater accumulation to have a negative effect. Saw gin production rates are usually not noticeably affected by honeydew contamination until the sugar content exceeds 0.40 percent by weight (Perkins and Bassett 1988). The 1977 and the 1986 cotton crops, which had sugar contents ranging from 0.25 to 0.40 percent (Perkins 1983, Perkins and Bassett 1988) and which caused major textile mill processing problems, did not cause any particular ginning problems that were attributable to stickiness. The sticky cotton problems of 1977 and 1986 were confined primarily to the San Joaquin Valley of California, and at that time there were no roller-gins in the Valley. However, the 1991 and 1992 sticky cottons were in Arizona, and some lots had sugar content as high as 0.56 percent or more by weight and caused serious ginning problems for not only roller- but also saw-gin plants.

The 1991 and 1992 sticky cotton problems in saw-gin plants manifested themselves by a buildup of loose lint and other materials on condenser screens, 6-cylinder cleaner bars, lint cleaner bars, seed cotton conveying piping, and other metal surfaces. Honeydew from contaminated seed cotton rubbed off onto various metal surfaces as the seed cotton and ginned lint were being processed. A condenser separates fiber from a conveying air stream at several stages in the ginning process. The buildup of material on condenser screens was one of the early indicators of a problem and would eventually plug up the screen so that air could not pass through. This would not allow seed cotton and lint to be conveyed, and the ginning process would have to be stopped until the screen was washed with soap and water. Once the contamination was removed, air could pass through and the process would start over again. The same scenario of contamination and method of removal was true for the other areas of honeydew accumulation in the saw-gin plant. Regardless of the location of the problem, honeydew accumulation resulted in loss of ginning production and increased ginning costs.

### **Recommendations for Ginning Sticky Cotton**

In 1990, USDA-ARS, Cotton Incorporated, and other groups initiated research to find ways to combat the sticky-cotton problem in the textile mill (Perkins et al. 1992). The increased seriousness of the problem for the ginning industry starting in 1991 caused

increased effort to find a solution (Hughes et al. 1994b). Because roller-gin stands are the most susceptible to honeydew contamination, ginning and textile research was focused on roller-ginned Pima cotton. A module of heavily honeydew-contaminated Pima S-6 from the 1992 harvest season was obtained from Arizona and used for all subsequent ginning tests at the Southwestern Cotton Ginning Research Laboratory. Research results showed that the best-performing methods of treating sticky seed cotton to improve ginning performance were heating and application of additives.

### **Heating**

Ambient weather conditions during the cotton harvest and ginning season across the cotton belt can be highly variable, leading to a wide range in relative humidity. Both constituents of seed cotton—fiber and seed—are hygroscopic, but at different levels (Hughes et al. 1994a). Dry cotton placed in damp air will gain moisture, and wet cotton placed in dry air will lose moisture. For every combination of ambient air temperature and relative humidity, there are corresponding equilibrium moisture contents for the seed cotton, fiber, and seed. For example, if seed cotton is placed in air of 50 percent relative humidity and 70 °F, the fibers will tend to reach a moisture content (wet basis) of approximately 6 percent; the seed will tend to reach a moisture content of about 9 percent; and the composite mass will approach a moisture content of 8 percent. The equilibrium moisture content at a given relative humidity is also a function of temperature and barometric pressure.

Seed cotton moisture and particularly fiber moisture are important when processing sticky cotton through a ginning system. Just as common table sugar is not sticky when it is kept dry, insect honeydew is not sticky below a certain moisture content. This aspect of insect honeydew is discussed in chapter 13.

Cotton known to be sticky was studied in a ginning experiment done to examine the effect on stickiness of drying it with heated ambient air. Under laboratory conditions, a roller-gin stand can be expected to produce 1.5 bales of Pima cotton fiber per hour. Table 1 shows the effect of drying seed cotton on roller-gin stand productivity. The seed-cotton drying choices for most gin plants range from no drying to two stages of drying at variable temperatures. No drying is used, particularly in the irrigated west, if the seed-cotton was

harvested after having been air-dried on the plant for a considerable time under clear, warm, low-humidity conditions.

The USDA-recommended moisture level for gin processing is 6 to 7 percent for saw-ginning upland cotton and 5 to 6 percent for roller-ginning Pima cotton (Gillum et al. 1994, Hughes et al. 1994a). Under normal conditions, the cotton shown in table 1 could have been processed without any further drying as shown by the average seed-cotton and lint moisture for the no-drying treatment. However, because of the presence of high levels of honeydew, the maximum average roller-ginning rate obtainable was only 0.76 bales/hour without any drying. This is about half the normal maximum ginning rate expected. The expected roller-ginning rate of approximately 1.5 bales/hour was not reached until the lint moisture content was reduced to about 4.5 percent. It was at the 4.5 percent moisture level that the honeydew no longer caused a sticking problem and the ginning rate was essentially normal. It is believed from these tests that the honeydew changes from a sticky form to a nonsticky form somewhere between 4.5 and 5.0 percent moisture content. Reducing the lint moisture content below 4.5 percent by more drying and higher temperature drying did not significantly increase the maximum ginning rate.

Heating cotton fiber during the ginning process to dry the honeydew and render it nonsticky has been shown to have only a temporary effect. The cottons shown in table 1 were carded at the Clemson Pilot Spinning Plant at nominal air conditions of 56 percent relative humidity and 76 °F. At this atmospheric condition, the moisture content of the fiber is approximately 6 to 7 percent (Griffin 1977). It was not possible to card any of the fiber from any of the heat treatments, indicating that the honeydew had reverted to its sticky form.

### **Additives**

Several chemical additives have been recommended as beneficial to the cotton ginning process and to fiber quality. Early trials evaluated three chemical additives—PC-3 Plus, Milube N-32, and HIIvol SCF—for reducing the effects of honeydew on cotton ginning and processing (Perkins et al. 1992). PC-3 Plus is a surfactant of proprietary formulation. Milube N-32 is a nonionic lubricant that contains both mineral oil and ethoxylated components at less than 1 percent by volume with other components held as a trade secret. HIIvol SCF is a proprietary aqueous blend of lubricants and emulsifiers that contains both mineral oil



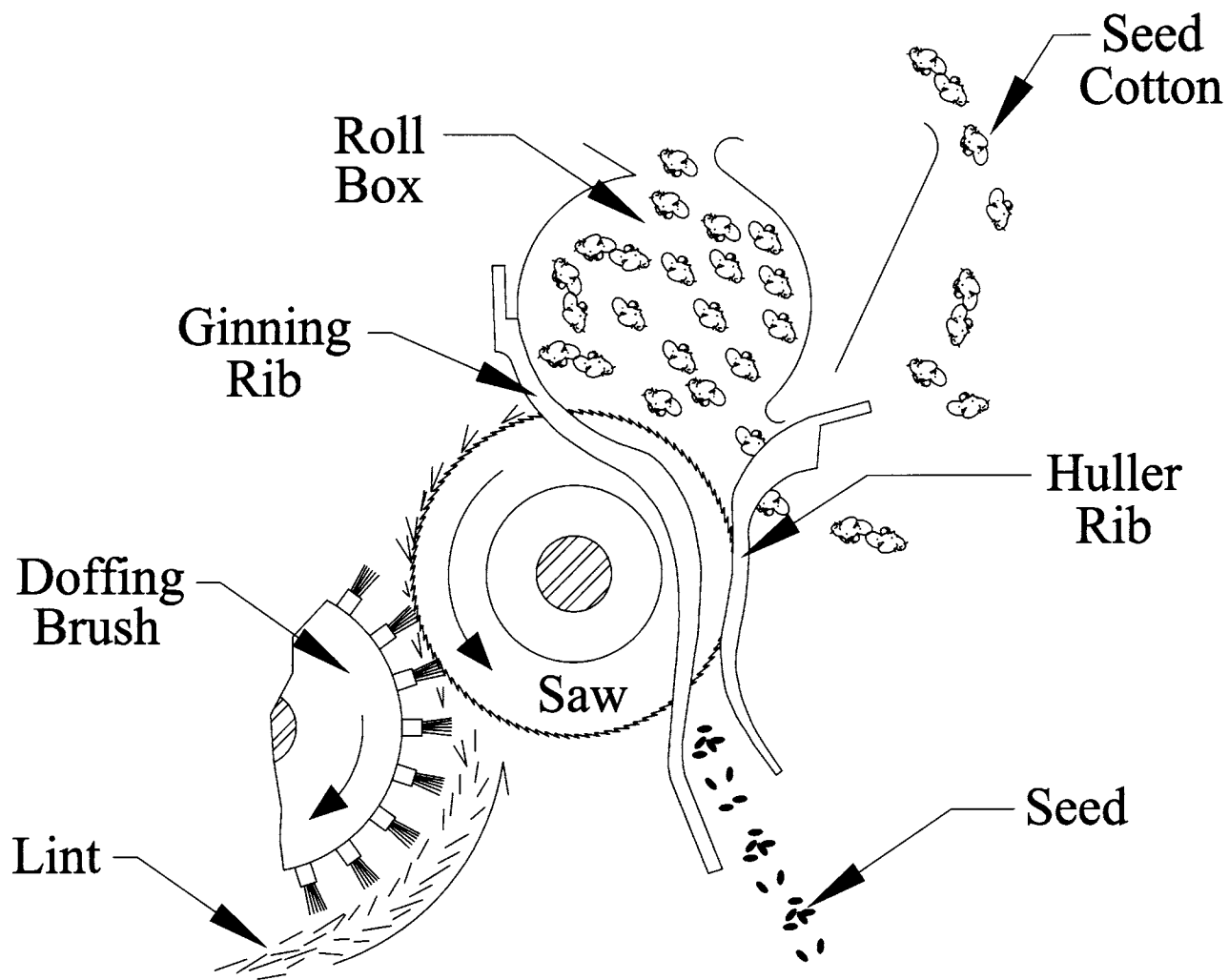


Figure 2. Generic saw-gin stand.

and ethoxylated components at less than 1 percent by volume. These preliminary trials indicated that Milube N-32 and HIIvol SCF reduced the effects of honeydew when processing cotton.

Table 2 shows the results of additional, comprehensive ginning tests of Milube N-32 and HIIvol SCF. The cotton was from the same module of Pima S-6 that was used to determine the effects of heating on honeydew. Each additive was sprayed onto the seed cotton immediately after seed-cotton cleaning and immediately before it was fed into the roller-gin stand. No drying was used during the additive testing, as indicated by the lint moisture contents shown in table 2. The untreated control was essentially the same as the control used for the heat treatment tests. Both HIIvol SCF and Milube N-32 showed positive effects (treatments 3 and 4) by increasing roller-ginning rates at application rates of 0.75 and 1.15 percent by weight of fiber. Neither additive was as effective in increasing ginning rate as was reducing lint moisture content to 4.5 percent by heating.

The cotton lint from the tests shown in table 2 were also sent to the Clemson Pilot Spinning Plant for evaluation on their carding system. None of the additive treatments could be carded even though additive application had significantly increased ginning production. Tests were done on the ginned lint at Clemson to determine the actual application rate that was achieved in the gin. Lint that had received treatment 3 (HIIvol SCF at 0.75 percent) and treatment 4 (Milube N-32 at 1.15 percent) averaged 0.17 and 0.14 percent additive by weight respectively. Increasing the actual application rate of Milube N-32 in the textile opening line to 0.6 percent only allowed marginal carding at 20.4 kg/hr, but the fiber could not be carded at the target rate of 27.2 kg/hr. With very sticky cotton, additives were fairly effective in aiding ginning but were only marginally effective in minimizing stickiness when applied ahead of the carding operation.

## Lint Cleaning

Honeydew from aphids and whiteflies falls on leaves and bolls. Since foliage occupies a greater area in the horizontal plane than does the exposed lint in open bolls, it is likely that the majority of the honeydew initially drops on the surfaces of leaves. The final location of honeydew is complicated by the fact that any individual leaf on an insect-infested plant can serve both as a recipient and as a source of honeydew.

Infested leaves directly above an open boll would drop most of their honeydew directly onto the boll. When cotton is machine-harvested, dried leaves that have not been removed by harvest-aid treatments are frequently shattered and mixed with the lint. Stickiness, as estimated by the sticky cotton thermodetector (SCT, described by Frydrych 1986) was higher in ginned lint with more leaf trash (Henneberry et al. 1997). Levels of trehalulose and melezitose, the two principal insect sugars causing stickiness, were higher in the trash from lint with higher trash content than in the trash from lint with lower trash content. These data suggest that stickier leaf trash more readily adheres to lint and may further contaminate it with carbohydrates causing stickiness.

Also, removing the sticky leaf trash was found in some instances to reduce stickiness as measured by the SCT (Henneberry et al. 1997). However, there was an interaction of lint cleaning treatment with the initial level of stickiness contamination. Cleaning moderately sticky lint (as classified by Perkins and Brushwood 1995) following ginning did not reduce stickiness as measured by the SCT. Cleaning highly sticky lint (Perkins and Brushwood 1995) reduced the SCT counts by about 20 percent, but the resulting lint was still highly sticky.

## Summary

Research has shown that under low-humidity (less than 30 percent) conditions, exposing seed cotton during cleaning to an air temperature of 148.9 °C or more allows a roller-gin stand to operate at normal throughput rates at least for short periods. For very sticky cottons in commercial ginning environments, there are long-term buildups of sticky materials that eventually require shutdown of ginning operation and manual cleaning before production can continue. The beneficial effects of heating on ginning, however, do not carry over to the textile mill, possibly because the sugars become sticky again when they rehydrate under higher humidity.

Two chemical additives, Milube N-32 and HIIvol SCF, were shown to allow relatively normal roller-ginning rates under relatively dry atmospheric conditions for at least short periods. Over the long term sticky materials from very sticky cottons still build up when these products are used. Other oil-based textile lubricants similar to Milube N-32 and HIIvol SCF would probably give similar results when applied in

the ginning process. As in heating, the benefits of a gin application of these additives at the levels shown are not likely to carry over to the textile mill. It would be unwise to apply even higher levels at the gin to try to increase the benefit to either the gin or the textile mill. Many textile mills already routinely apply textile lubricants as part of their normal process. If the mill does not know that there is already textile lubricant on the ginned fiber, there is danger of over-application of the lubricant.

The saw-ginning process is not as sensitive to the effects of sticky cotton as is roller-ginning. Occasionally some very sticky Pima cotton that can not be ginned even when using heat and chemical additives must be saw-ginned. This decreases the value of the Pima cotton. Anecdotal evidence says that when saw-gins are having problems ginning very sticky upland cottons, heating the cotton to dry the fiber and applying chemical additives also have a beneficial effect on the saw-ginning process.

**Table 1. Heat treatment effects**

Drying level and temperature	Ginning rate	Moisture content	
		Module seed-cotton	Lint
°F (°C)	bales/hr	----- % (dry basis)-----	
1: 86 (30) <sup>a</sup>	0.76	5.76	5.40
2: 200 (93.3)	0.89	5.20	5.14
3: 300 (148.9)	1.55	5.42	4.48
4: 400 (204.4)	1.62	5.78	4.32
5: 350 (176.7) & 400 (204.4)	1.67	5.09	3.29

<sup>a</sup> No drying—average ambient temperature

**Table 2. Effects of additives on ginning sticky cotton**

Treatment	Additive	Concentration weight <sup>a</sup>	Ginning rate content	Lint moisture
		%	bales/hr	%
1	None	-	0.70	5.16
2	Milube N-32	0.75	0.86	4.96
3	HIIvol SCF	0.75	1.27	4.87
4	Milube N-32	1.15	1.19	4.99

<sup>a</sup> Weight of additive applied as a percentage of weight of ginned lint processed.

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## Chapter 12

### Sticky Cotton Sampling

*S.E. Naranjo and E.F. Hequet*

Sampling is a fundamental component of any research program and is an essential element for accurately measuring and quantifying the characteristics of cotton lint quality for both research and commercial grading purposes. A sample is a set of “sample units” that allows one to make inferences about the entire population from which these observations are drawn. Sampling activities are guided by a structured set of rules called a sampling plan or program. The sampling plan includes the designation of the sample unit, how sample units are spatially allocated among potential sample units in the population, and how many sample units will be collected for each sample in order to get a reliable mean estimate.

In sampling for lint stickiness there may be different goals depending on the stage at which observations are made (for example, field, gin, or textile mill). Crop monitoring during the season and use of decision-making tools to aid in determining the need for sweetpotato whitefly (or cotton aphid) control to prevent sticky cotton development (chapter 7) or the use of remedial actions to reduce or eliminate stickiness (chapter 10) could potentially allow growers to produce high quality lint and avoid price penalties. Estimation of stickiness in harvested cotton is an obvious consideration for the textile manufacturer to prevent costly machinery downtime and excessive machinery maintenance. At what stage or stages in the crop production lint stickiness should be determined remains an open question. Overall, the most critical issue for cotton producers and textile manufacturers is that, wherever the sticky cotton determination is made, it accurately predict possible textile processing problems.

#### Stickiness Measurement Systems

Sampling for lint stickiness is a two-stage process: (1) collection of sample units from the field, module, or bale and (2) assay of these sample units to provide a quantitative measurement of stickiness. There are a

number of different measurement systems that have been developed to qualitatively or quantitatively assess lint stickiness (chapter 13; see also Hector and Hodkinson 1989).

The sampling methods and plans that will be described here are limited to three physically based measurement systems; however, the approaches and analyses would be similar regardless of measurement methodology. These systems include the manual sticky cotton thermodetector (SCT) which is currently the method recommended by the International Textile Manufacturer’s Federation for measuring cotton stickiness (Perkins and Brushwood 1995), the high speed stickiness detector (H2SD) (Hequet et al. 1997), and the fiber contamination tester (FCT) (Mor 1996). The SCT involves spreading a thin web of conditioned lint between aluminum foil sheets, heating under pressure, separating the aluminum foil sheets, and counting the number of adhering sticky spots (Brushwood and Perkins 1993). The H2SD, with a few minor modifications, essentially duplicates the process of the SCT on an automated basis, greatly speeding sample throughput. For the FCT a fiber sliver, whose mass and length is fixed, is fed into a microcard. The web that is formed passes between two heated drums under pressure. The sticky spots adhering to the drum are counted with an image analyzer. More detail is provided in chapter 13.

The measurement instrument employed is a significant factor in the development of any sampling plan. For example, a plan developed for the SCT is not directly applicable to the H2SD because each platform has its own inherent error characteristics and variability.

#### Sampling for Cotton Lint Stickiness

There has been considerable research and development of methods and machinery for the measurement of lint stickiness. However, very little research has addressed the basic issues of sampling and the development of sampling plans for the accurate estimation of stickiness. In this chapter we will provide a detailed summary of our current knowledge of sampling for lint stickiness at both preharvest and postharvest stages in the cotton production and processing cycle.

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## Data Sources and General Methods

The data in support of preharvest field sampling work was collected from central Arizona and southern California between 1995 and 1999. Over this period, data was collected using a variety of different sample units from a total of 87 field sites, some of which included samples from the same field on several different dates. In most cases we also determined the amount of time necessary to collect each sample unit for further analyses of sampling efficiency. Seed cotton from these field sample units was ginned using a small research gin, and following hand blending a subsample was then assayed using the SCT or the H2SD, or both, depending on the amount of lint available and the underlying objectives of the project each year. All H2SD assays were completed by the International Textile Center at Texas Tech University in Lubbock, TX; most SCT assays were done at the USDA-ARS laboratory in Clemson, SC. In general, three replicate assays were conducted on both instruments.

Several studies have been conducted at the International Textile Center to evaluate postharvest methods for estimating cotton stickiness in bales and modules. In one experiment, 50 Texas bales representing a range of stickiness were selected. Ten 1-pound sample units were taken per bale, and for each sample unit three replicate assays were conducted on FCT, H2SD, and SCT instruments at several locations. A second experiment was conducted following the same sampling protocol on 100 bales coming from California and Arizona that were selected to represent a large range of stickiness. To further define within-module variability, a third study was undertaken consisting of 283 modules from Arizona and California. For each module a single sample unit (similar to the grader's sample, about one-half pound of lint) was taken from three bales for each module. Three replicate assays were conducted for each sample unit on the H2SD.

### Comparison of Sample Units

Proper selection of the sample unit can reduce bias by ensuring that the unit is representative of the universe (a field, for example) being sampled. Further, selecting the sample unit that minimizes both variance and cost can optimize the efficiency of sampling. All of the sample units we evaluated for field sampling here are representative of the sample universe, but differed in the level and extent of aggregation (table

1). Whole-plant sample units are unbiased because they encompass all of the lint on a single or multiple plants that represent quantifiable units of the entire field. Boll sample units also are unbiased because the individual bolls in any one sample unit (for example, 20 or 40 bolls) are selected at random within the crop canopy and again represent a quantifiable unit of the habitat. In bale or module sampling the goal was to develop sampling protocols that are compatible with current grader sampling methods. Thus, the sample unit was not the subject of further experimental work and consisted of at least 4 ounces of lint taken from each side of the bale.

For field sampling we generally found that regardless of the size of the sample unit, ranging from lint collected from 20 open bolls at random (1 boll per plant) to all of the lint on 30 consecutive plants (table 1), mean estimates of stickiness were essentially the same using either the SCT or H2SD platforms. However, from the perspective of sampling efficiency, the best sample unit is the one that provides the highest level of precision or repeatability for the lowest cost. Larger sample units sometimes had comparatively lower variance, but they were more time-consuming, and thus more costly, to collect from the field. Southwood (1978) suggested that the relative net precision (RNP) of a sample unit should be proportional to  $1/(C_u S_u)$ , where  $C_u$  is the cost per capita of the sample unit and  $S_u$  is a measure of sample unit's relative variability. Higher values of RNP indicate a more efficient sample unit (better precision at a lower cost). Here we use the coefficient of variation ( $CV = SD/mean$ ) to represent relative variation and sample collection time in the field to estimate costs per unit. Based on results averaged over 5 years, the 1-plant sample unit was most efficient, followed by the 20-boll sample unit for both assay platforms. This tells us that smaller sampling units are more efficient than larger units. Further discussion on field sampling will focus only on the 1-plant and 20-boll sample units.

### Sampling Distributions

We contrasted the sampling distributions of thermodetector counts from the SCT and the H2SD for field samples and from the SCT, H2SD, and the FCT for bale and module samples. We calculated the coefficient of dispersion (CD), estimated as the ratio between the sample variance and sample mean, to characterize the between-assay and between-sample unit sampling distributions. Generally,

CD < 1 indicates a regular distribution, CD ≈ 1 indicates a random or Poisson distribution, and CD > 1 indicates an aggregated or clumped distribution. For field samples we found that CDs between replicate assays (within-assay) indicated a more regular to random distribution for the SCT, but an aggregated distribution for the H2SD (table 2). Likewise, CDs for between-sample unit counts were lower for SCT than the H2SD and again indicated a random distribution for the SCT and an aggregated distribution for the H2SD (table 2).

Based on studies conducted on Sudanese commercial cotton bales, Fonteneau Tamine et al. (2000) found that the CD of stickiness readings using the H2SD was approximately 4.84, leading the authors to reject the hypothesis of a Poisson distribution. The authors fitted the data to an empirical model that relates the mean to the variance. This empirical model indicated an aggregated distribution.

Based on sampling studies of bales from Texas, it appears that all within-assay CD's are well above 1, revealing an aggregated distribution (table 3). The mean CD values were close to 2 for the H2SD and SCT instruments tested. Assays on the FCT revealed an even more aggregated distribution, suggesting inconsistent results on this instrument. Except for the FCT, the within-bale CD's are all around 1. Thus, the variability within a bale is smaller than the variability within a sample unit. Similar conclusions can be drawn from the second set of bale samples from Arizona and California (table 4). Consequently, for U.S. cottons, it appears that the regular classer's sample unit should be representative of the entire bale. A final study to evaluate within-module variability showed that the within-assay CDs averaged 1.5, revealing a slight overdispersion relative to a Poisson distribution (table 5). The within-module CD averaged 2.8, revealing that the variance of stickiness readings within a module is roughly twice the variance within a bale. This indicates that classification of stickiness based on module averaging is not feasible because of the large degree of variability in stickiness within a module.

Module averaging consists of testing each bale, averaging all of the bales from the same module, then applying this average value to each individual bale. In doing this we could incur the risk of overestimating or underestimating the stickiness value of the individual

bales. This may have an extremely negative effect on both producers and spinners. The overestimated bales will be discounted with no reason and the underestimated bales will lead to cotton mixes with a higher than desired stickiness level. Consequently, we cannot envisage module averaging for stickiness based on a single grader's sample unit per bale; thus, each bale should be tested individually.

## Partitioning of Variance Components

Thermodetector assays are conducted on lint from a field or bale sample unit. Thus, there are two sources of variation: (1) variability among replicate assays from individual sample units and (2) variability among sample units collected from the same field or bale. Because the sampler can exert some level of control over both of these sources of variation, we quantified and evaluated their contributions to overall sample variation. Nested ANOVA was used to partition and quantify within- and between-sample unit variability for a set of samples assayed on the SCT and the H2SD. For the SCT we found that approximately 57 percent of the variation was attributable to differences among field sample units (field variation) while the remaining 43 percent represented between-assay variability (laboratory variation). This latter source of variation for the SCT includes variability caused by subsampling and the SCT operator. Because the H2SD largely eliminates operator error we would expect the laboratory component of variation to decline. Instead we found that nearly 70 percent of the total variance was attributable to between-assay error for the H2SD, while only 30 percent was attributable to field variation. The probable cause for this result will be explained below under "Other Sources of Variation."

This variance partitioning analysis can be used to determine the optimal allocation of sampling effort between the field and laboratory components (Cochran 1977, Southwood 1978) as—

$$N_L = (C_F S_L / C_L S_F)^{0.5}$$

where:

$N_L$  is the laboratory sample size,  
 $C_F$  is the cost per unit of field sampling,  
 $C_L$  is the cost per unit lab assay,  
 $S_F$  is the field variance, and  
 $S_L$  is the laboratory variance.

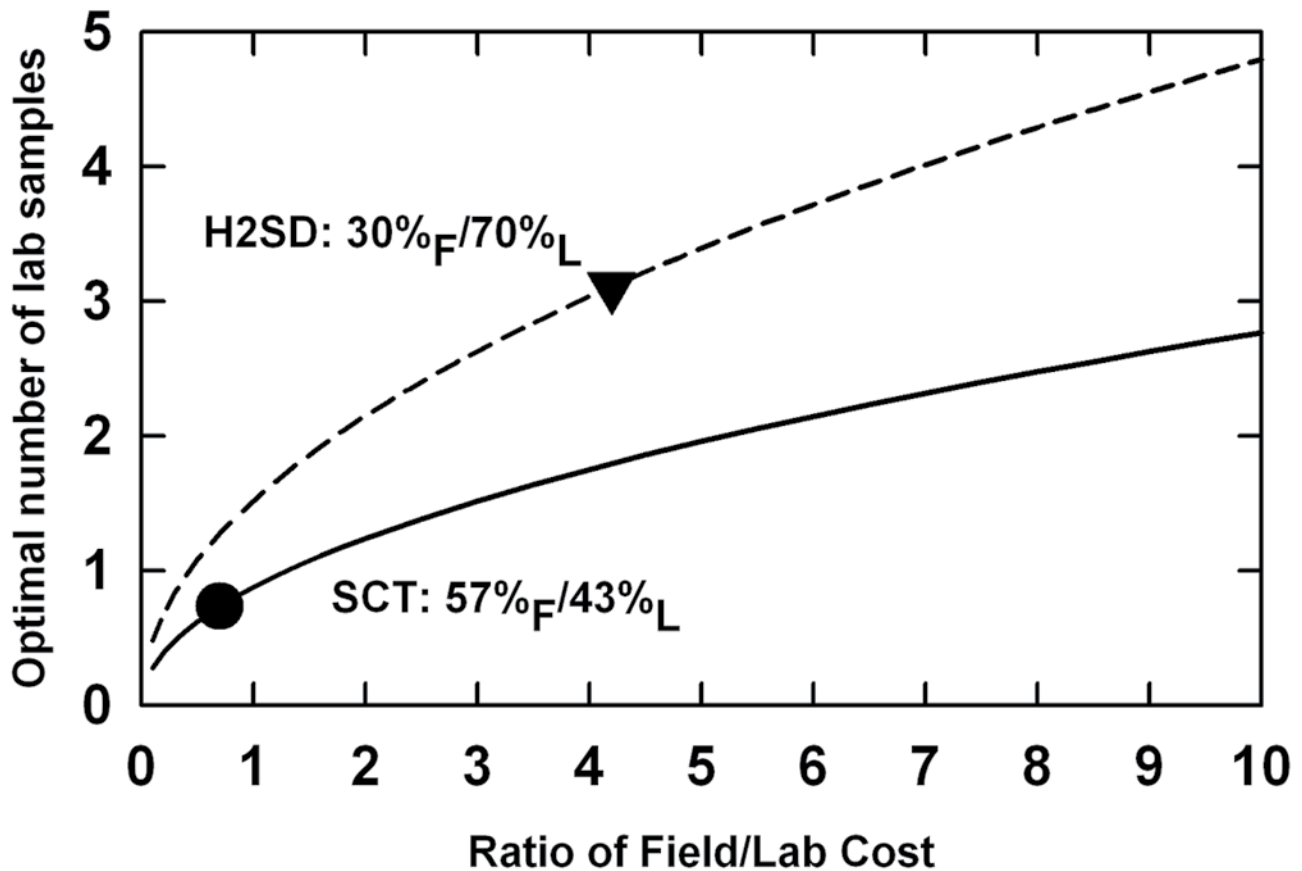


Figure 1. Components of variation and implications for sampling effort allocation relative to costs. The symbols denote the optimal number of laboratory assays from each field sample unit based on known field collection costs and the assumption that single H2SD and SCT assays take 0.5 and 3 min, respectively, to complete. Results based on 20-boll sample units collected during 1998-99.

Using this approach we calculated the optimal number of replicate assays necessary to minimize variance in relation to cost (figure 1). Assuming a field cost of about 2 minutes per unit ( for a 20-boll sample unit) and an SCT assay cost of 3 minutes, this analysis suggests that only a single assay should be conducted on each sample unit (figure 1, circle on the solid line). Assuming a field cost of 2 minutes per unit and an H2SD assay cost of 0.5 minutes, our analysis suggests that 3 assays should be conducted on each sample unit (triangle on dotted line). These analytical results follow directly from the more qualitative patterns shown in table 2 and simple cost considerations. The more regular distribution of counts between assays for the SCT and the high cost of assay suggest that sampling effort is better spent on the collection of the more variable field sample units rather than replicate assays on each unit. The reverse is essentially true for the

H2SD, for which sampling distributions are aggregated for both assay and field, but assay costs are much lower than field collection costs. Interestingly, our results for the H2SD agree with standard assay protocols already in place for the SCT and H2SD, which call for 3 replicate assays for each sample unit.

### Other Sources of Variation

There are additional sources of variation that can influence the estimation of lint stickiness. Two of these are worthy of further discussion here: variation between laboratories conducting the assays, and the degree of preparation of lint samples prior to assay. During field studies conducted in 1996, samples (20-boll sample unit) collected from 18 different field sites were subsequently assayed on SCT platforms run by two different laboratories. A nested ANOVA of



square-root transformed counts was used to estimate the variance component due to differences between laboratories within the context of within- and between-sample-unit variability as described above. Results pooled over all field sites indicated that only about 9 percent of the total variation was attributable to differences between laboratories. However, despite this relatively small amount of variability, further analyses demonstrated significant differences in mean spot counts among the 18 fields (figure 2). Further, there was a consistent pattern in the difference between the two laboratories, with higher spot counts being reported by one laboratory and differences being greater with increased average spot counts. In the absence of a standardized test methodology, and more importantly of standards to calibrate the instruments, this type of difference is to be expected.

USDA uses a very careful procedure to pick the cotton used for HVI (high volume instrument) calibration. The following is an extract from “The Classification of Cotton” (USDA/AMS 1993): “As a first step the USDA conducts an intensive search for the most

uniform bales of cotton in the current crop. Candidate bales are screened for uniformity of fiber quality by testing 12 samples drawn from throughout each bale. Bales that pass this preliminary screening then undergo detailed analysis to determine whether they meet USDA standards for certification and use as calibration cottons.” None of this exists for stickiness, and thus it makes between-laboratory comparisons extremely difficult. Still, it does emphasize the potential importance of human and perhaps machine error in the assay process. Based solely on sampling distributions, it would appear that there is relatively little variation between different laboratories using the SCT and only minor variation with the H2SD for stickiness estimation in bale sampling (see tables 3 and 4).

Another source of variation concerns the degree of lint cleaning before a sample is assayed. This is unlikely to be an important factor for commercially ginned seed cotton, or for classing samples, but small research gins used by researchers generally have no capacity for cleaning lint to efficiently remove seed fragments, leaf trash, and other debris. We evaluated the effects

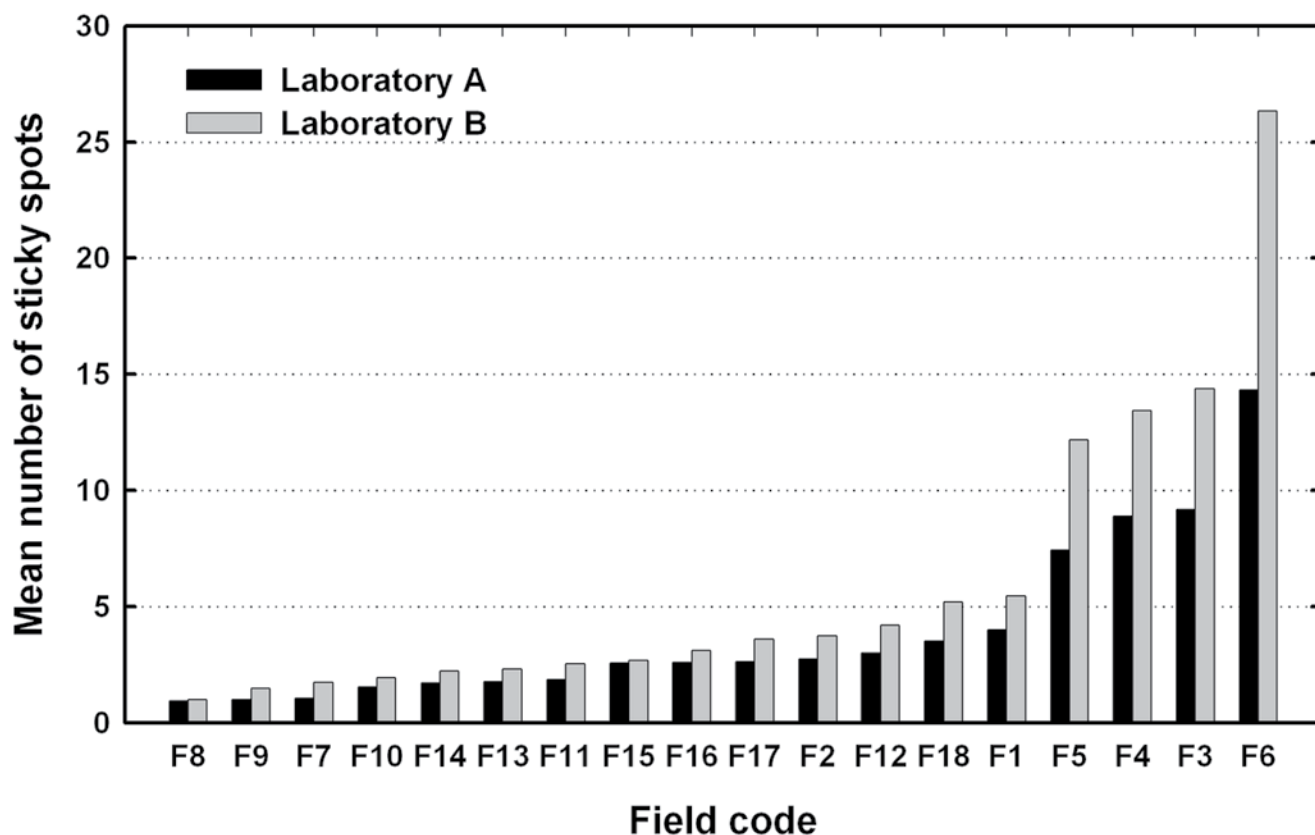


Figure 2. Comparison of stickiness estimates for 18 fields between two laboratories using the SCT instrument.

of lint cleaning on spot counts and variability for 32 samples collected from the field in 1998 and 1999. Prior to assay on both the SCT and the H2SD, ginned (research gin) samples were either subjected to further cleaning or not. Samples to be cleaned were processed through a single pass of the Shirley Analyser. Three replicate assays were performed on each instrument. We found essentially no change in sampling characteristics from the SCT as a result of lint cleaning (table 6). On average, there was no significant change in the magnitude of the SCT reading and measures of sampling distributions (CD) changed very little. Conversely, lint cleaning had a dramatic effect on the sampling characteristics from the H2SD. Cleaning reduced the average spot count by more than 30 percent, and the between-assay sampling distribution changed from aggregated to random (table 6). Cleaning did not significantly alter the size distribution of spots ( $\chi^2 = 1.86, P = 0.39$ ); overall, 66, 15, and 17 percent of the spots were categorized as small, medium, and large, respectively. The automated platform would appear to be more sensitive to lint trash and other impurities, which results in higher and more variable counts between assays. The lack of change with cleaning in the SCT suggests that some trash is removed from the samples during sample preparation and that the technician is able to more readily differentiate spots caused by sticky lint rather from those caused lint trash. For the H2SD it suggests that sampling properties can be greatly altered by lint cleaning and that consistent protocols need to be followed in comparative research studies where cleaning capacity may or may not be available.

### Sampling Plans for SCT and H2SD Platforms

The sampling plan is a procedure for collecting a sample from the field or from a module or bale and arriving at an estimate of stickiness with a desired level of repeatability and accuracy. This includes the sample unit (in the case of field sampling) used to take samples, the number of sample units to collect, the processing of the seed cotton, the assay platform, and the number of replicate assays to perform. Here we assume that 3 replicate assays will be performed on each sample unit.

The two remaining elements required to complete a sampling plan for estimating lint stickiness are the interrelated factors of sample size and precision. For this we use an empirical model that allows the estimation of the sample variance based on the sample

mean. We used Iwao's patchiness regression (Iwao 1968) to describe the relationship between the sample mean and variance. Sample size curves were estimated for two levels of precision (figure 3) using the general relationship:

$$N = (t_{\alpha/2}/D)^2(s^2/m^2),$$

where:

N is sample size,  
 t is Student's t for a specified  $\alpha$  (type I error rate),  
 D is a fixed proportion of the true mean,  
 m is the sample mean, and  
 $s^2$  is sample variance estimated from the empirical model.

The cost of sampling was estimated by multiplying the sample size by the per unit costs of sample collection and assay as discussed above. For bale sampling we estimated the sample collection costs at 1 minute per unit. Specific examples of sample size and cost are presented in table 7 for four levels of precision. For example, given a true mean of 10 sticky spots on the SCT, a sample size of 23-25 would permit us to estimate a mean between 9 and 11 with 95 percent confidence. A sample size of 58 would be required to make the same estimate from bales samples using the H2SD. Regardless of precision, it can be seen that sample size requirements decline as levels of stickiness increase. The level of precision desired also influences sample size requirements dramatically, with lower levels of precision requiring many fewer sample units. For field sampling, the speed of the H2SD results in generally lower sampling costs despite higher sample size requirements, especially at lower levels of precision. The 20-boll sample unit appears to be more cost-efficient for field sampling. Overall, the sample size chosen by the user will depend on an interplay between cost considerations and how much precision and accuracy is required in determining levels of stickiness.

Another way to examine the relationship between sample size and precision is to ask, "What sample size would be needed to confidently distinguish levels of stickiness between two cottons?" This is a critical issue if stickiness is to become a standard measure of lint quality. We can address this question by calculating statistical power ( $1-\beta$ ) where  $\beta$  is the Type II error, the probability of accepting a false null hypothesis. The greater the power, the greater is our ability to confidently distinguish between two alternatives.

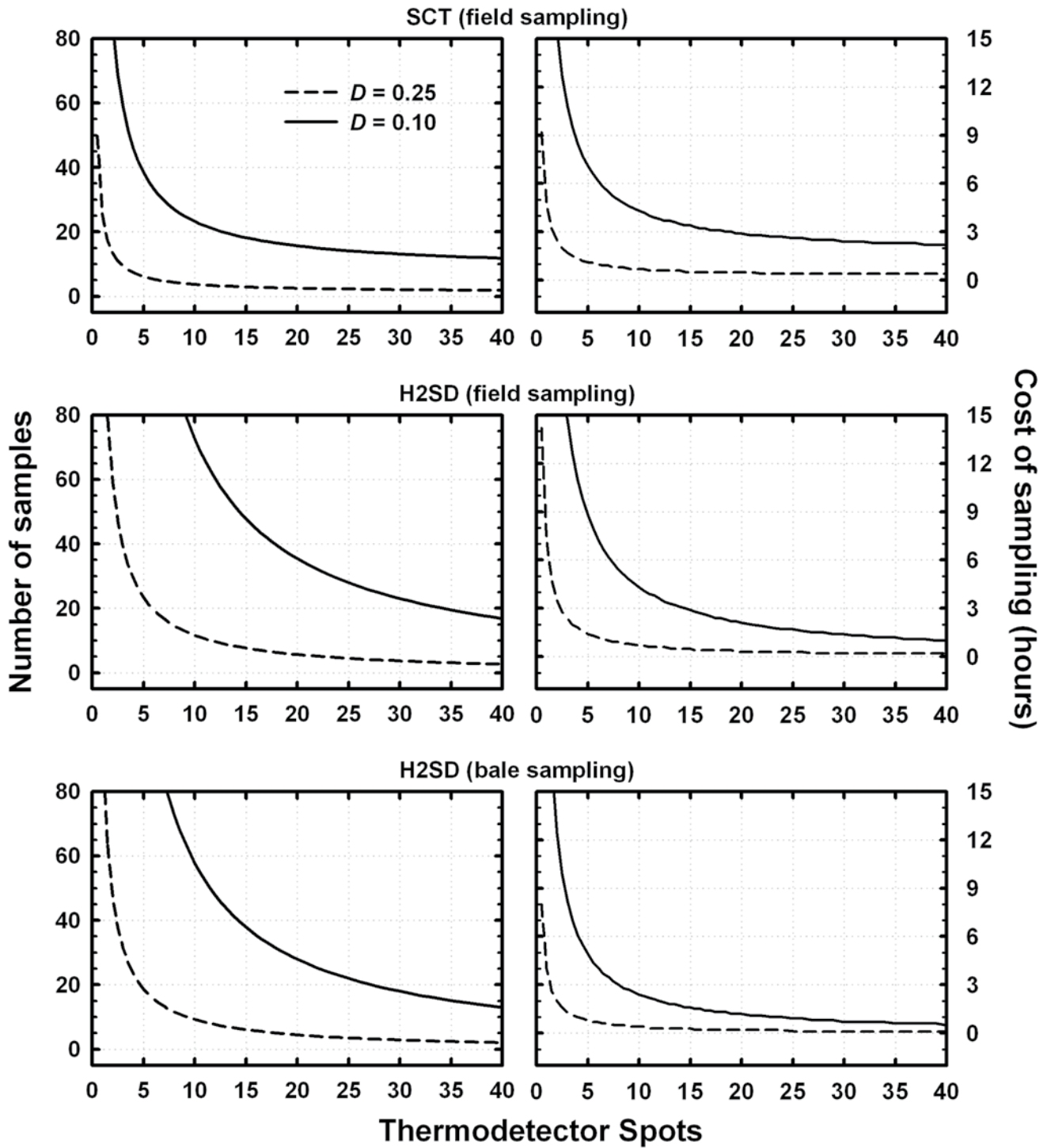


Figure 3. Sample sizes and sampling costs required to estimate mean stickiness with two levels of precision (expressed as a fixed proportion of the mean with 95% confidence) on two assay instruments and assuming a mean-variance relationship described by Iwao's patchiness regression. Field sample sizes are based on a 20-boll sample unit. Bales samples are based on a grader's sample unit. See text for details.

To determine power we need to define  $\alpha$ , the Type I error rate, and  $\delta$ , the numerical difference we wish to distinguish. Here, we set  $\alpha = 0.05$  and let  $\delta$  vary. We also need to square-root-transform the data to normalize the intrasample variance.

We will assume here that a spot count of around 10 represents the division between nonsticky and sticky lint and examine sampling properties associated with this level of stickiness. In figure 4 we plot statistical power for field sampling as a function of sample size for different levels of  $\delta$ , the spot count difference that we can expect to detect when the true mean is 10 on the SCT. With a  $\delta = 0.5$  on a square-root scale, a relatively large sample size would be required for an adequate level of power ( $> 90$  percent). For example, a sample size of about 16 would be needed to discriminate two samples with arithmetic sticky counts of 7.1 and 13.4 with a power of 90 percent. Low sample sizes can provide high power but only at low levels of resolution. For instance, a sample size of 5 would be expected to discriminate two samples with counts of 1.4 and 26.6 spots, on an arithmetic scale, with 90 percent power. As noted above, the sample size chosen by the user will depend on cost considerations and the goals of the sampling program. For example, relatively low power and resolution may be adequate for a researcher interested in distinguishing between two alternative control methods for suppressing sweetpotato whiteflies in the field. Alternatively, very high power and resolution will be needed for determining stickiness as part of lint quality assessment. This latter issue is explored in more detail below.

From the bale and module sampling results presented above (“Sampling Distribution”), it is clear that the FCT exhibits a higher level of variability than both the SCT and the H2SD. Furthermore, even if the variability of the SCT is acceptable, from a practical point of view, its usage is, and will remain, extremely limited (because of, for example, operator effect or use of a manual instrument). Consequently, the H2SD appears to be a better candidate for large-scale testing of lint quality. Here we calculate power curves for the H2SD using data from the 100 bales from Arizona and California discussed above. Figure 5 shows that to discriminate between 2 samples with 90 percent power, 6 replications would be necessary with  $\delta = 1$ , 4 replications with  $\delta = 2$ , and 3 replications with  $\delta = 3$ .

Another way to examine this problem is to define two categories, sticky and nonsticky. For the purpose of this

demonstration we assume that the threshold between sticky and nonsticky is 10. Let’s further assume that we have a bale with a H2SD spot count of six. Is this count statistically below 10 sticky spots? The answer to this question with an average sample size of 6 is yes with a power of 80 percent (figure 6). A sample size of 9 from the same bale with 6 sticky spots is statistically below 10 spots with a power of 90 percent (figure 6).

## Relationship Between Preharvest and Postharvest Stickiness

Although preharvest sampling may serve several goals as discussed previously, it is of interest to understand the relationship between these field estimates of stickiness and those determined from harvested cotton. Over the course of the field studies described here we often collected subsamples of lint after machine harvesting. Typically these were collected immediately or within 1 day after collecting the final in-field samples. Linear regression analysis was used to describe the relationship between the stickiness of final field samples and harvest samples after square root transformations of both counts. For the SCT the regression model is given as [*In-field*  $\times$  0.79] + 1.01 ( $r^2 = 0.55$ ,  $n = 53$ ), indicating that harvest stickiness was consistently higher than stickiness measured from samples drawn from the field, at least for mean stickiness levels less than 25 on an arithmetic scale. The mean difference in counts was about 0.5 on a square-root scale. For the H2SD the regression model is given as [*In-field*  $\times$  1.01] + 2.96 ( $r^2 = 0.71$ ,  $n = 24$ ) indicating that harvest stickiness was consistently higher than stickiness determined from field samples at all levels of stickiness. Here, the mean difference in spot counts was about 3 on a square-root scale. The reason for these consistent differences is unclear but could be related the spreading and mixing of honeydew droplets or possibly the addition of insect sugars from stems and leaf parts during the harvest process. In any case, our results suggest that field sampling may slightly underestimate stickiness of the harvested lint and more research may be needed to evaluate this issue.

## Sequential and Classification Sampling

Sampling plans for the estimation of lint stickiness or the categorization of stickiness could potentially be made more efficient through the use of what are known as sequential sampling plans. Such plans are commonly used in entomology for both research purposes and for decision-making in integrated pest management

(Binns et al. 2000). Both efficiency and precision are optimized because in sequential sampling the need for further sample information is assessed following the collection of each individual sample unit. For the estimation of a mean, the method ensures that no more sample units are collected than necessary in order to achieve a predetermined level of precision. Further, because in most cases sample size decreases with increasing means (figure 4) the method automatically ensures that the correct number of sample units are collected without any prior knowledge of the mean. Sequential sampling for mean estimation operates by accumulating counts (in this case sticky spots) over subsequent sample units and then consulting a cumulative count curve or a table to determine the need for more sample units or the termination of sampling. Once sampling is terminated, the mean is calculated by simply dividing the cumulative count by the number of sample units collected.

Operationally, the method would be most simple for single-stage sampling in which the count can be made immediately after collecting the sample unit (for example, counting whitefly adults on cotton leaves). Because stickiness sampling is a two-stage process requiring laboratory assay, sampling for stickiness in the field would require that the user collect a set number of sample units. However, a sequential plan could then be implemented at the assay stage, ensuring that only as many sample units as necessary be processed to meet a predetermined precision. With the SCT, which requires approximately 3 minutes to complete a single assay, substantial time could potentially be saved. Less time would be saved using a faster platform (such as the H2SD), but sequential sampling may still prove a valuable cost-saving approach. Cost saving could be even more significant for bale testing because the first stage of sampling

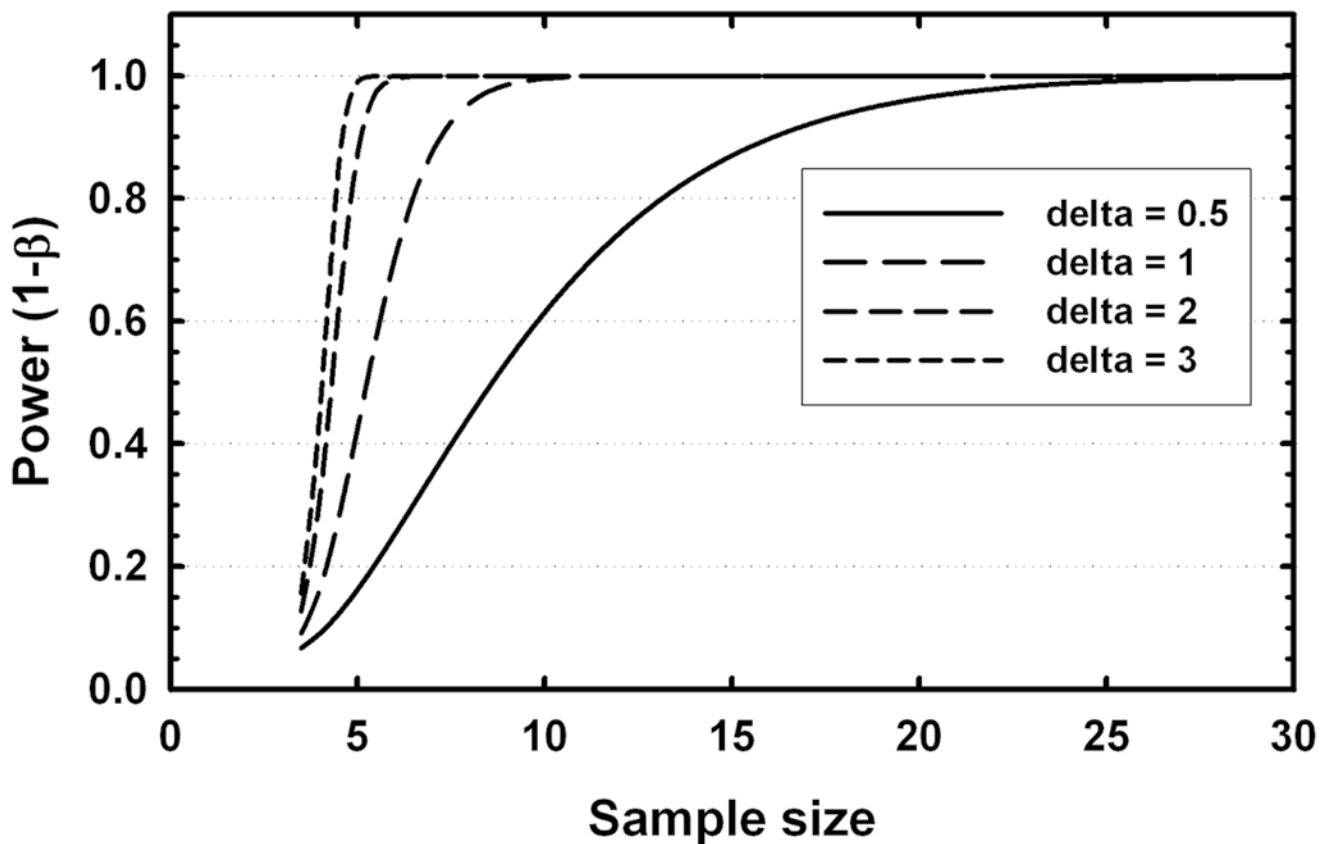


Figure 4. Statistical power for square-root transformed SCT spot counts from field samples as a function of sample size for various levels of delta, the difference we can expect to detect when the true mean is 10 on an arithmetic scale (2-tailed [ $\mu = \mu_0$ ] with  $\alpha = 0.05$  and  $\sigma^2 = 0.241$ ).

(lint collection) is much quicker and in some instances the assay machinery may be near the lint source (gin, textile mill, classing office, etc.).

A second application of sequential sampling involves the classification of lint stickiness rather than estimation of mean stickiness levels per se. In the case where one simply wants to determine whether lint is sticky or nonsticky, a sequential classification approach could save substantial time and effort. Operationally, the method is similar to that described above for mean estimation except that a critical density must be specified. In insect control this critical density would be the economic threshold. Densities above the critical density would require control; densities below would require no action. For sticky cotton it would be the level of stickiness delineating two classes of stickiness, be it the difference between nonsticky and lightly sticky or the difference between lightly and moderately sticky.

To demonstrate this approach, let's assume that 10 sticky spots is the critical threshold. Several approaches have been described for sequential classification sampling. Here we will apply the method developed by Wald known as the sequential probability ratio test (Binns et al. 2000). For field sampling using the SCT we will assume a Poisson sampling distribution. For bale sampling using the H2SD we used the Taylor Power Law ( $s^2 = am^b$ ) to estimate the relationship between the mean ( $m$ ) and variance ( $s^2$ ). We further set Type I and II error rates to 0.05, set the minimum sample size to 1, and use the simulation methods of Binns et al. (2000) to evaluate the sampling plan.

Results are shown in figure 7 for three different maximum sample sizes (3, 10, and 25) on each instrument. The average sample number simply shows the sample size that would be required to classify lint stickiness as a function of the level of stickiness. What is immediately clear is that very few sample units are

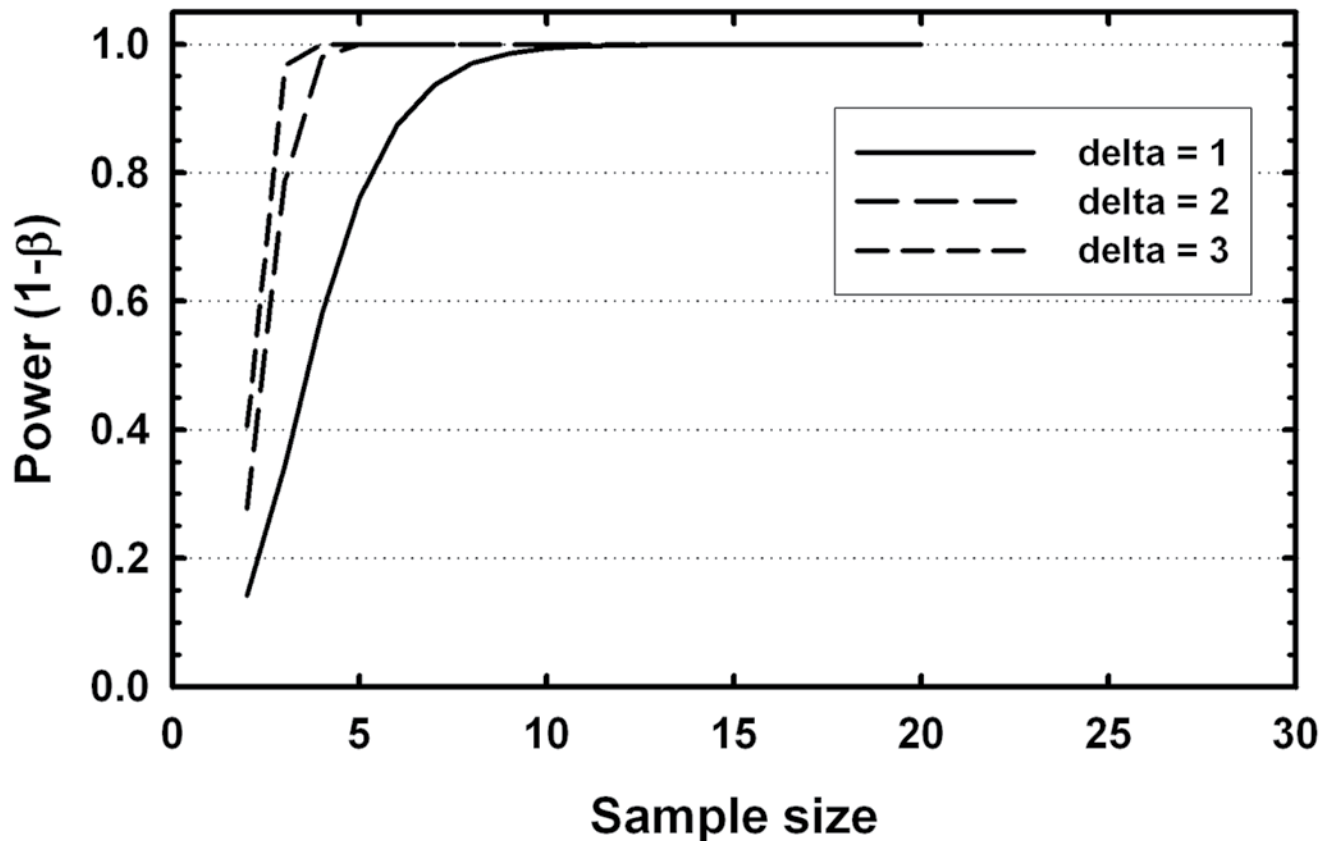


Figure 5. Statistical power for square-root transformed H2SD spot counts from bale samples as a function of sample size for various levels of delta, the difference we can expect to detect when the true mean is 10 on an arithmetic scale (2-tailed [ $\mu = \mu_0$ ] with  $\alpha = 0.05$  and  $\sigma^2 = 0.392$ ).

required when stickiness is below or above 10 spots, but that a relatively large sample size is required when stickiness is at or near this critical density. The steepness and width of the sample size curve about the critical density depends on the maximum sample size. The operating characteristic shows the probability of classifying the lint as nonsticky as a function of the number of sticky spots. Ideally, this curve would be vertical at the critical density resulting in perfect discrimination between sticky and nonsticky cotton. In reality, there is the possibility of misclassification, with greater error associated with lower maximum sample sizes and changes in other sampling parameters (not shown). For example, with a maximum sample size of 25, readings below about 9.6 and above about 10.5 would be classified correctly as nonsticky or sticky, respectively. These boundaries widen as maximum sample size declines. Samples with a mean stickiness

very near 10 will be misclassified roughly 50 percent of the time. The Poisson distribution of the field SCT data results in narrower sample size functions compared with the aggregated distributions of the bale H2SD data. However, there is relatively little difference in the error curves.

This approach demonstrates that sampling efficiency could be improved dramatically by ensuring that maximal effort is expended only when lint stickiness is near the critical density. Classification of lint stickiness outside this narrow range would require very little effort. Again, the implementation of such a plan would depend on the goals and purpose of sampling. Such an approach may still be unfeasible for classing purposes under current sampling protocols, but it may be useful for research purposes where more time and effort can be devoted to sampling.

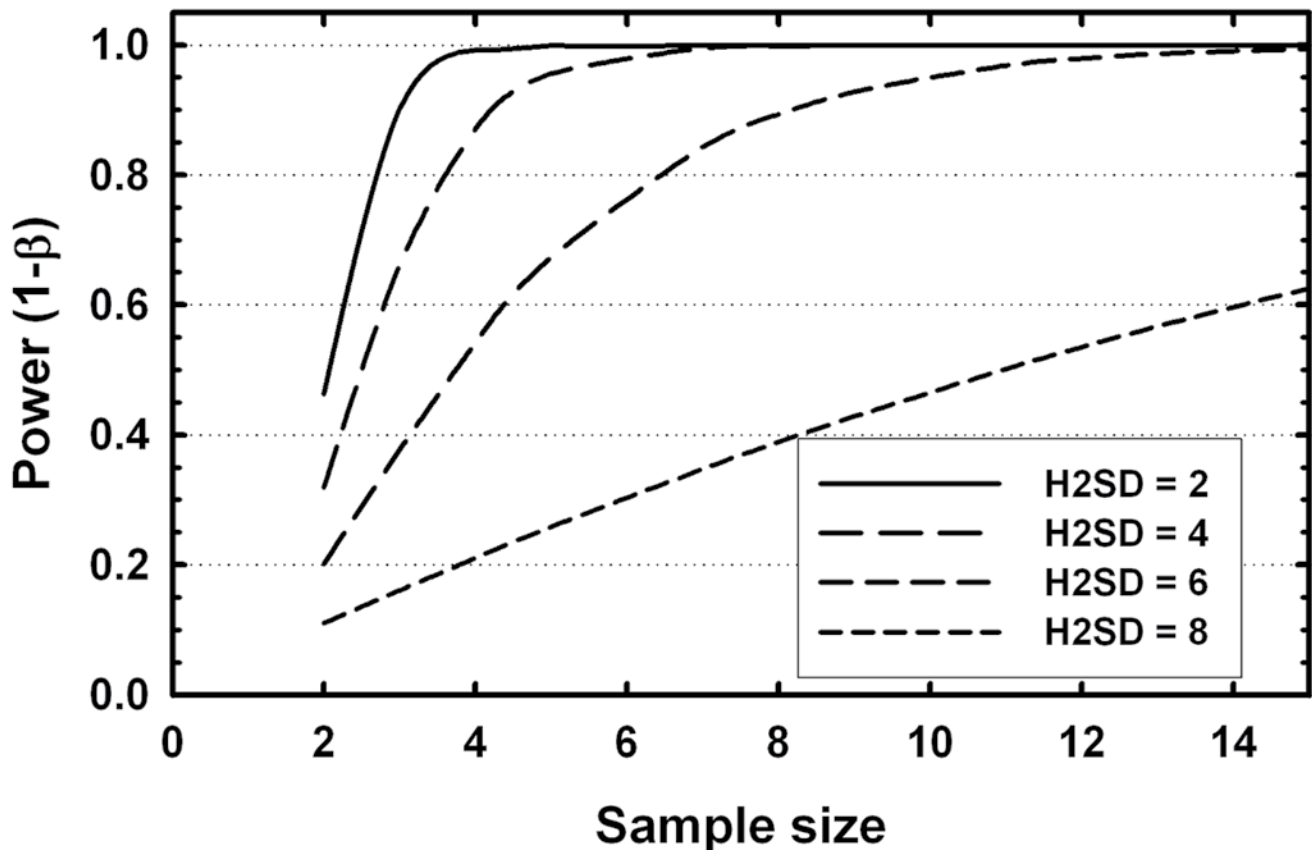


Figure 6. Statistical power for square-root transformed H2SD spot counts from bale samples as a function of sample size for various differences in stickiness from a true mean of 10 on an arithmetic scale (1-tailed [ $\mu \geq \mu_0$ ] with  $\alpha = 0.05$  and  $\sigma^2 = 0.392$ ).

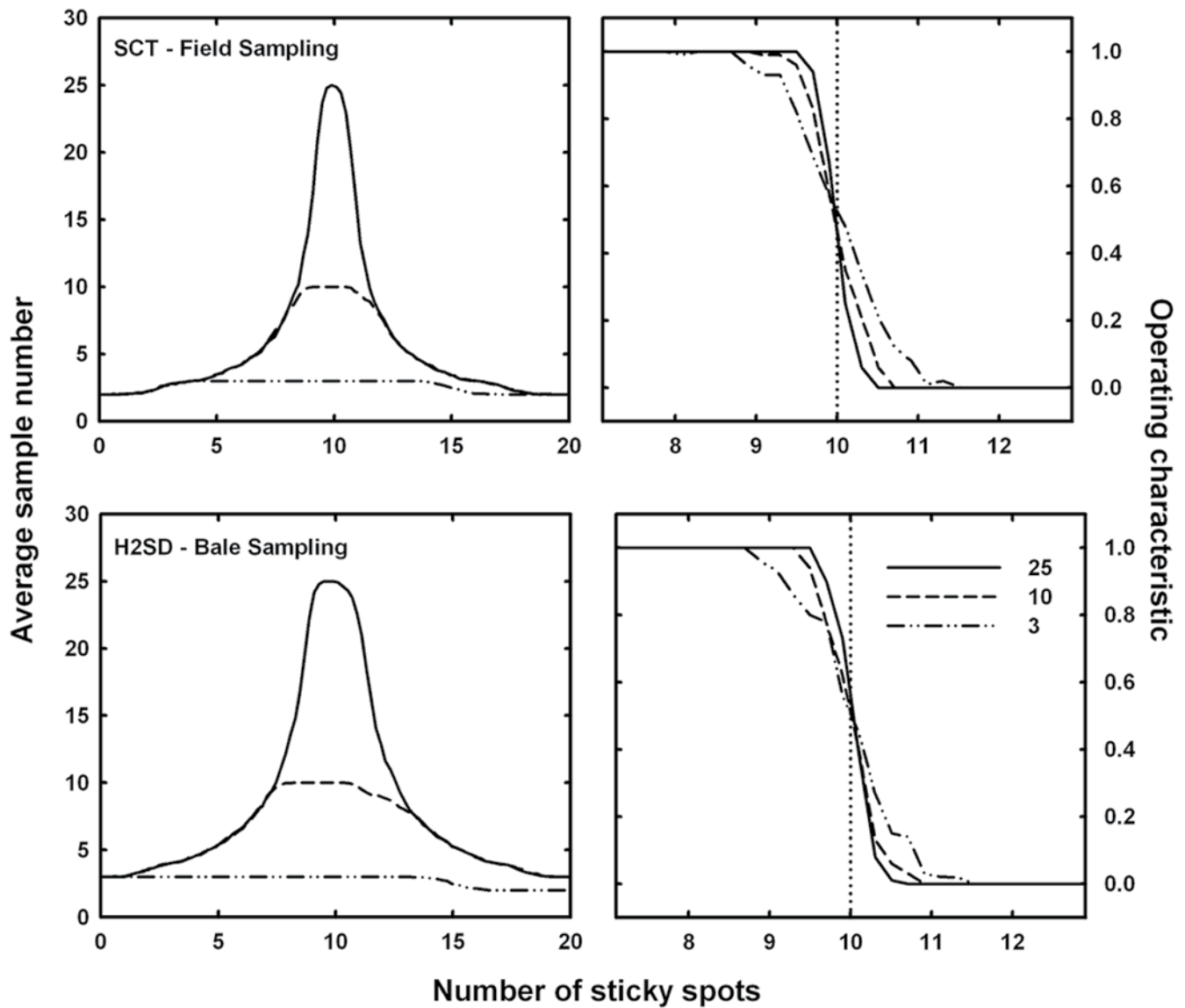


Figure 7. Performance of various sequential sampling plans for classifying lint stickiness from field and bale samples assayed on SCT and H2SD instruments. This example assumes that 10 sticky spots is the critical boundary between sticky and nonsticky lint. The average sample number simply shows the required sample size as a function of stickiness levels. Sample size requirements are maximal near the critical boundary. The operating characteristic gives the probability of classifying the lint as nonsticky as a function of stickiness levels. An ideal curve would be vertical at 10 as denoted by the dotted line. The lines represent a maximum sample size of 3, 10, or 25.



## Conclusions and Future Developments

Here we have presented a detailed summary of our current knowledge of sampling for lint stickiness at both preharvest and postharvest stages of production and suggest sampling protocols for two measurement instruments. Relative to a grader's sample, the precise estimation of lint stickiness using either the SCT or the H2SD requires considerably more effort regardless of whether the determination is made directly from within-field samples or from harvested modules or bales. The FCT has shown even greater variability, and we did not pursue the development of sampling plans for this instrument.

Depending on the level of precision desired and the level of lint stickiness, as many as 23 sample units or as few as 2 sample units may be required to estimate stickiness of field-collected lint on the SCT. An equivalent range for the H2SD is 73 to 3 sample units for field sampling and 58 to 2 sample units for bale sampling. While these sampling requirements may be feasible for research purposes in the field, gin, or textile mill, they are clearly unsuitable for lint quality assessment in a commercial setting. It is simply not feasible with current thermodetection technology to delineate sticky from nonsticky cotton with acceptable power and precision using a grader's bale sampling method, which consists of a single sample unit that is assayed in triplicate. The use of module averaging, in which stickiness is determined from sampling of multiple bales per module and then assigning that level of stickiness to each bale is also unfeasible. Our results show that variability between bales in a module is even larger than within-bale variability. This system could incur the risk of overestimating or underestimating the stickiness value of the individual bales.

It is also very unlikely that producers could effectively use in-field sampling for assessing the dynamics of lint stickiness in their production systems. Even though sample size requirements for field sampling of stickiness are modest compared to requirements for most insect pest sampling (for example, see Naranjo 1996), the time necessary to collect an adequate sample are relatively large and currently there is the additional constraint of limited access to testing machinery. The application of a sequential sampling protocol could enhance the efficiency of sampling for research purposes, but even the simple classification of stickiness would require more effort than grader's

sampling for sufficient confidence in the classification outcome.

Although we did not explore the sampling properties of other stickiness testing methods, including chemically based tests, our overall conclusions regarding commercial feasibility are unlikely to change. Regardless of whether samples are collected from the field or from modules or bales, stickiness of ginned lint is simply too variable to achieve reasonable precision with only a single or a few sample units, especially when stickiness levels are between 0 and 10. One practical alternative would be to develop an online assay system that could accommodate the throughput necessary to test a larger number of sample units. The current mechanically based systems discussed here would be impractical for this purpose, but perhaps some type of spectroscopic measurement (or example, Fourier-transform infrared spectroscopy or Raman spectroscopy [chapter 13]) would be rapid enough. Whether or not such systems can be used to estimate stickiness is currently unknown; however, there are several laboratories in the United States examining the potential of Fourier-transform infrared spectroscopic analysis for this purpose.

**Table 1. Summary of field sample units examined 1995-1999 using manual (SCT) and automated high-speed (H2SD) sticky cotton thermodetectors**

Sample unit	Cost per unit <sup>a</sup> minutes	SCT		H2SD	
		RNP <sup>b</sup>	<i>n</i>	RNP <sup>b</sup>	<i>n</i>
1 Plant	1.40	0.031	29	0.033	6
2 Plants	2.18	0.016	35	–	–
5 Plants	4.51	0.010	22	–	–
10 Plants	8.40	0.005	22	–	–
20 Plants	16.17	0.003	22	–	–
30 Plants	23.95	0.002	17	–	–
20 Bolls	2.08	0.018	55	0.026	38
40 Bolls	3.54	0.015	26	0.019	21
50 Bolls	4.27	0.010	15	0.013	10
80 Bolls	6.45	0.017	5	–	–
100 Bolls	7.91	0.011	5	–	–
200 Bolls	15.20	0.005	5	–	–

<sup>a</sup> Cost in time to collect sample unit in the field.

<sup>b</sup> Relative net precision ( $1/[(SD/mean) \times \text{cost}]$ ) measures the relationship between relative variability and cost; higher values indicate a more efficient sample unit.

**Table 2. Coefficients of dispersion (variance/mean) for 3 replicate assays on each instrument and for sample units collected from the same field**

[All samples collected 1998-1999 using 20-boll and 1-plant sample units]

	Instrument	Coefficient of dispersion			<i>n</i>
		Median	Maximum	Minimum	
Within assay	SCT	0.62	8.24	0.00	320
	H2SD	2.53	84.79	0.00	320
Between samples	SCT	1.04	4.30	0.08	44
	H2SD	3.24	9.96	0.46	44

**Table 3. Coefficients of dispersion (variance/mean) calculated on 50 bales from Texas for three types of instruments (SCT, FCT and H2SD) at three laboratories**

[10 sample units per bale with 3 replicate assays per sample unit]

	Instrument	Laboratory	Coefficient of dispersion		
			Mean	Minimum	Maximum
Within assay	FCT	A	5.8	0.0	77.3
	H2SD	B	2.4	0.0	21.5
	SCT	B	2.6	0.0	23.6
	SCT	C	2.6	0.0	36.6
Within bale	FCT	A	2.2	0.8	8.7
	H2SD	B	0.6	0.1	1.4
	SCT	B	0.7	0.1	1.4
	SCT	C	1.3	0.1	8.7

**Table 4. Coefficients of dispersion (variance/mean) calculated on 100 bales from Arizona and California for three types of instruments (FCT, H2SD and SCT) at two laboratories**

[10 sample units per bale with 3 replicate assays per sample unit]

	Instrument	Laboratory	Coefficient of dispersion		
			Mean	Minimum	Maximum
Within assay	FCT	D	6.7	0.0	541.2
	H2SD	D	2.7	0.0	35.6
	H2SD	B	2.1	0.0	14.3
	SCT	B	2.7	0.0	33.9
Within bale	FCT	D	4.4	0.3	112.4
	H2SD	D	2.7	0.1	30.1
	H2SD	B	0.9	0.1	4.4
	SCT	B	1.7	0.1	9.0

**Table 5. Coefficients of dispersion (variance/mean) calculated on 283 modules from Arizona and California for one type of instrument (H2SD) at one laboratory**

[1 sample unit from each of 3 bales per module with 3 replicate assays per sample unit]

	Instrument	Laboratory	Coefficient of dispersion		
			Mean	Minimum	Maximum
Within assay	H2SD	D	1.5	0.0	11.9
Within module	H2SD	D	2.8	0.0	67.7

**Table 6. Comparison of stickiness estimates and variability on cleaned and raw lint assayed by SCT and H2SD**

	SCT		H2SD	
	Raw	Clean	Raw	Clean
Range <sup>a</sup>	1.3-14.3	0.3-18.0	3.3-71.0	0.7-65.0
Median CD <sup>b</sup>	0.48	0.50	2.01	0.87
Mean % change from raw	–	-1.41	31.61	–
<i>t</i> <sup>c</sup>	–	0.22	9.22	–
P	–	0.83	<0.01	–

<sup>a</sup> Range of spot counts (untransformed) for the 32 samples.

<sup>b</sup> CD: coefficient of dispersion (variance/mean) for replicate assays.

<sup>c</sup> *t*-test to evaluate the null hypothesis that the mean % change in spot count = 0

**Table 7. Sample sizes required to estimate various levels of mean stickiness with various levels of precision using different sample units on two assay platforms.**

[Results expressed as a fixed proportion of the mean with 95% confidence and assume a mean-variance relationship described by Iwao's (1968) patchiness regression. Numbers in parentheses are estimates of the total time (hours) required to complete sampling, including both field or bale and laboratory]

Precision	Mean sticky spot count			
	10	20	30	40
SCT (1-plant unit)				
0.1	25 (4.4)	17 (2.8)	13 (2.3)	12 (2.0)
0.15	11 (2.0)	7 (1.3)	6 (1.0)	5 (0.9)
0.2	6 (1.1)	4 (0.7)	3 (0.6)	3 (0.5)
0.25	4 (0.7)	3 (0.5)	2 (0.4)	2 (0.3)
SCT (20-boll unit)				
0.1	23 (4.3)	16 (2.9)	13 (2.4)	12 (2.2)
0.15	10 (1.9)	7 (1.3)	6 (1.1)	5 (1.0)
0.2	6 (1.1)	4 (0.7)	3 (0.6)	3 (0.5)
0.25	4 (0.7)	3 (0.5)	2 (0.4)	2 (0.4)
H2SD (1-plant unit)				
0.1	155 (7.5)	73 (3.5)	45 (2.2)	31 (1.5)
0.15	69 (3.3)	32 (1.6)	20 (1.0)	14 (0.7)
0.2	39 (1.9)	18 (0.9)	11 (0.5)	8 (0.4)
0.25	25 (1.2)	12 (0.6)	7 (0.3)	5 (0.2)
H2SD (20-boll unit)				
0.1	73 (4.3)	35 (2.1)	23 (1.4)	17 (1.0)
0.15	32 (1.9)	16 (0.9)	10 (0.6)	7 (0.4)
0.2	18 (1.1)	9 (0.5)	6 (0.3)	4 (0.3)
0.25	12 (0.7)	6 (0.3)	4 (0.2)	3 (0.2)
H2SD (bales)				
0.1	58 (2.4)	28 (1.2)	18 (0.7)	13 (0.5)
0.15	26 (1.1)	12 (0.5)	8 (0.3)	6 (0.2)
0.2	15 (0.6)	7 (0.3)	5 (0.2)	3 (0.1)
0.25	9 (0.4)	5 (0.2)	3 (0.1)	2 (0.1)

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## Chapter 13

### Measurement of Stickiness

*E.F. Hequet, N. Abidi, G.R. Gamble, and M.D. Watson*

In the late 1970's, cotton stickiness testing was essentially based on the common belief that cotton stickiness corresponded to the content of reducing sugars. Reducing sugars are distinguished by having a free aldehyde or ketone group. Cotton fibers are mostly (88.0 to 96.5 percent)  $\alpha$ -cellulose (Basra and Saha 1999), and it is generally accepted that sucrose, the major translocated sugar via the phloem tissues (Tarczinski 1992), is the main source of carbon supplied to the fibers. Consequently, all of the intermediate compounds produced during the biosynthesis of cellulose from sucrose may be found on cotton fibers or within the lumen. This means that cotton lint, at the field level prior to harvest, contains sugars. Although it is rare, their complete removal is possible by either weathering or microbial activity (Perkins 1993).

The most common sugars associated with cotton fibers are glucose, fructose, and sucrose. Glucose and fructose are both monosaccharides. All monosaccharides are reducing sugars: They all have a free reactive carbonyl group. Some disaccharides have exposed carbonyl groups and are therefore also reducing sugars. Sucrose is a disaccharide and is classified as a nonreducing sugar. The presence of sucrose in the cotton lint reveals that the plant was still growing at harvest—some sucrose was still being translocated to the bolls in order to continue the growth process and to accumulate cellulose within the underdeveloped fibers. It is thought that the fiber of mature bolls would have a low physiological sugar content, while immature bolls, still in the development phase, would have a high physiological sugar content. Also, it is suspected that harvest-aid chemicals may cause some of these immature bolls to open. For this type of cotton plant the distribution of the sugars in the bolls will not be even. The least developed fibers coming from such immature bolls tend to remain together in the form of entangled fibers. When ginned, because of the water content of this specific type of fiber, the physiological sugars can migrate from the inside to the outside of the fiber through the open lumen (Hequet and Ethridge 1999). This succession of events can lead to a localized concentration of sugars. Elsner (1983) showed that cutting bolls off the cotton plant did not stop the

metabolism of the sugars present in the fibers. When bolls open, drying competes with the biochemical process of cellulose biosynthesis. Quick-drying of the fibers, whether by the misuse of harvest aids or by freezing, may promote high sugar content. This is rare.

The other source of sugar on the lint is insects. This is by far the most common source of sugar contamination. The composition of insect honeydew is quite complex. Hendrix et al. (1995) reported that only a few of the sugars in sweetpotato whitefly or cotton aphid honeydew are found in the insect diet; most sugars in these secretions are produced by the insect from phloem sap. Among such sugars, melezitose and trehalulose are specific to insects and are not found in the plant. The presence of these sugars on the lint reveals that the lint contamination comes, at least partially, from insect honeydew. Melezitose is a nonreducing trisaccharide. Trehalulose, a disaccharide, is an isomer of sucrose, and behaves as a reducing sugar under specific conditions of oxidation.

### Chemical Tests

#### Oxidation-Reduction Methods

Oxidation-reduction tests are performed on a water extract of the cotton fibers, generally with an added surfactant. These methods evaluate all water-soluble reducing substances present and not only the reducing sugars. The choice of the oxidizing agent has a large effect on the end result. A strong oxidizing agent will react with more reducing substances in the water extract under test than a weak oxidizing agent. This is especially important for trehalulose, which will remain undetected when using a weak oxidizing agent.

#### Potassium Ferricyanide Method (Perkins Method)

The potassium ferricyanide method (Perkins 1971a,b), sometimes identified in the literature as the USDA test or the Perkins test, is one of several methods based on the oxidation of reducing sugars currently used to screen cotton for potential stickiness. It is perhaps the most widely accepted of such methods for the quantitative determination of reducing sugars on cotton because it is simple, reproducible, and fast. Historically, the ferricyanide reducing-sugar test was developed in order to screen for stickiness caused by plant physiological sugars (glucose, fructose, and sucrose).

The test procedure consists of reacting a water extract of cotton with excess potassium ferricyanide in the presence of sodium carbonate. The ferricyanide anion oxidizes reducing substances in the extract, principally sugars, and is thereby reduced to ferrocyanide. The amount of ferrocyanide thus formed is quantified by titration with ceric sulfate dissolved in sulfuric acid solution. The titration end point is indicated by tris(1,10-phenanthroline)-iron(II) sulfate, which turns from red to faint blue upon oxidation. Though the reduction of ferricyanide by the reducing substances present is not stoichiometric, the method can be calibrated against known quantities of glucose. The quantity of sugar on cotton fiber thus determined has been correlated with stickiness problems arising in processing of contaminated cotton (Brushwood and Perkins 1993a,b).

This test was initially used for screening cotton for plant sugars, primarily glucose, fructose, and sucrose. Sucrose is not a reducing sugar, but glucose and fructose are, and together they account for most of the extractable physiological sugar present on cotton lint. The ferricyanide test thus gives a good correlation between reducing sugars and total sugars when these sugars are of plant origin. Insect honeydew comprises these same sugars plus an additional number of oligosaccharides including trehalulose and melezitose. With the exception of trehalulose, most of these oligosaccharides are nonreducing. As a result, the ferricyanide test does not provide a reliable correlation between reducing sugars and total insect sugars. This is especially so in the case of aphid honeydew, which contains little or no trehalulose (Hendrix 1999). As a consequence, the results of the ferricyanide test must be interpreted with some discretion and in conjunction with other known variables, such as region of growth where specific honeydew producing insect pests may predominate.

Other reducing-sugar tests have been used to evaluate honeydew contamination of cotton lint (Merkulova and Bashmakova 1986, Hector and Hodkinson 1989) even though it has long been realized that reducing-sugar content and lint stickiness are sometimes not well correlated. In spite of the lack of a strong correlation, some authors consider that reducing-sugar tests have value in screening for heavily contaminated cottons (Hector and Hodkinson 1989) and, in fact, for some sticky cotton samples a good correlation between reducing-sugar content and stickiness has been reported. For example, in comparing results of physical

stickiness methods and reducing-sugar methods on cottons from growing areas where stickiness was a significant problem in the 1992 U.S. crop, Brushwood and Perkins (1993a,b) noted a high correlation between lint reducing-sugar content and stickiness. It should also be noted that high reducing-sugar content in cotton fiber is considered a negative quality factor because (1) it is an indicator of chronic stickiness problems in textile processing such as residue buildup on rolls of processing machinery and in rotors of open end spinning frames and (2) reducing sugars are a significant contributor to the weight loss experienced by cotton yarn and fabric in textile wet processing. Perkins (1993) reported that the physical stickiness test methods (SCT, minicard, etc.) are generally ineffective in detecting this type of quality deficiency.

### **Fehling Test**

Fehling's solution (deep-blue alkaline solution) is used to test for the presence of aldehydes (such as formaldehyde, HCHO) or other compounds that contain the aldehyde functional group,  $-CHO$ . The substance to be tested is heated with Fehling's solution; formation of a brick-red precipitate indicates the presence of the aldehyde group. Simple sugars such as glucose give a positive test, so the solution has been used to test for the presence of glucose in urine, a symptom of diabetes.

Fehling's solution is prepared just before use by mixing equal volumes of two previously prepared solutions, one containing about 70 g/L of cupric sulfate pentahydrate and the other containing about 350 g/L of potassium sodium tartrate tetrahydrate and 100 g/L of sodium hydroxide. The cupric ion (complexed with tartrate ion) is reduced to cuprous ion by the aldehyde (which is oxidized) and precipitates as red cuprous oxide ( $Cu_2O$ ).

### **Benedict Test**

Benedict's solution (deep-blue alkaline solution) is also used to test for the presence of the aldehyde functional group,  $-CHO$ . The substance to be tested is heated with Benedict's solution; formation of a brick-red precipitate indicates presence of the aldehyde group. Since simple sugars like glucose give a positive test, this solution is also used to test for the presence of glucose in urine, a symptom of diabetes. One liter of Benedict's solution contains 173 grams of sodium citrate, 100 grams of sodium carbonate, and 17.3 grams of cupric sulfate pentahydrate. It reacts chemically like Fehling's solution: The cupric ion (complexed with citrate ions)



is reduced to cuprous ion by the aldehyde group (which is oxidized), and precipitates as red cuprous oxide,  $\text{Cu}_2\text{O}$ .

As shown above, Fehling and Benedict tests are based on the same principle. In the Benedict test the sugar content is estimated from the color of the solution as follows:

Blue	Very low
Green	Low
Yellow	Moderate
Orange to red	High

A large number of variations of this procedure are in use in different parts of the world. One consists of spraying the Benedict solution on the surface of a cotton sample. The sample is then placed in a microwave oven for 30 seconds to 2 minutes to allow the reaction. The evaluation of the color change is subjective as for the Benedict test.

Another variation is the Clinitest method in which Clinitest tablets (commercially available to test for glucose in urine) are used as a source of the cupric ion.

### **Bremen Honeydew Test**

The "bremen honeydew test" (Sisman and Shenek 1984) is one of the numerous complexing methods. The complexing methods involve the formation of colored compounds from the treatment of the water extract of cotton with strong acid to hydrolyze the sugars. The resulting monosaccharides are then reacted with an aromatic compound to form colored complexes. There are a number of aromatic molecules suitable for carrying out this reaction.

In the bremen honeydew test, a water extract of cotton is treated with 3,5-dihydroxytoluene in concentrated sulfuric acid. The intensity of the red complex formed is proportional to the amount of sugars or hydrolysable carbohydrates present.

A common problem with the complexing methods is the color of the water extract of cotton. The colored extracts could interfere with the readings and for some of them the nonspecificity of the chemical reaction could bias the results.

To our knowledge none of the complexing methods are in use to any extent today.

## **Enzymatic Tests**

Several enzymatic methods have been used for the determination of sugars on cotton. One reported quantitative method (Bailey et al. 1982) uses a series of enzymatic reactions on a water extract of cotton to convert sucrose, fructose, and glucose to glucose-6-phosphate. Glucose-6-phosphate then reacts with nicotinamide-adenine dinucleotide phosphate ( $\text{NADP}^+$ ) in the presence of glucose-6-phosphate dehydrogenase to form NADPH. NADPH is subsequently measured spectroscopically at 340 nm to give a direct correlation with total glucose, fructose, and sucrose content of the cotton extract. This method is not widely used because of its complexity, cost, and the fact that it does not provide a measurement of other oligosaccharides present in insect honeydew.

A relatively simple enzymatic test for glucose, developed initially to monitor blood glucose levels by diabetics, has been employed (Talpay 1983) as a test of sugar levels in cotton extracts for many years. Extracted glucose is reacted with glucose oxidase, producing hydrogen peroxide as a byproduct. The hydrogen peroxide is subsequently reacted with a colorless dye, which is oxidized to a blue color. The color intensity is proportional to the amount of glucose initially present.

A similar method (Gunasingham 1989) is based on the reaction of glucose oxidase with glucose, where the glucose oxidase is immobilized between two membrane layers. The glucose substrate is oxidized as it enters the enzyme layer, producing hydrogen peroxide, which passes through a cellulose acetate membrane to a platinum electrode where it is oxidized. The resulting current is proportional to the concentration of glucose.

The primary disadvantage of both of these methods is that glucose is the only sugar measured, and the correlation of glucose content with stickiness potential is marginal at best. A much better correlation is obtained (Gamble 2001) when the cotton extract is subjected to an acid hydrolysis treatment whereby all of the oligosaccharides present in the cotton extract are cleaved to their substituent monosaccharide units. When hydrolyzed, larger oligosaccharides obtained from sweetpotato whitefly and cotton aphid honeydew when feeding upon cotton are about ninety percent glucose (Hendrix 1999). Thus, a measure of total glucose following hydrolysis may be significantly correlated with total sugar content.

## Chromatographic Methods

The main advantage of the chromatographic methods is that they usually measure individual sugars rather than total sugars. The main disadvantages are that they are slow and equipment is expensive. These methods are not intended to test cotton for marketing purposes or for process control. Nevertheless, they are useful in research as a tool to better understand the origin of the stickiness phenomenon.

Paper chromatography and thin layer chromatography were used in the early stages of the cotton stickiness research (Bourelly et al. 1984). They were quickly supplanted by gas chromatography (GC) and more recently by high performance liquid chromatography (HPLC). Sweeley et al. (1963) described methods for making volatile derivatives of sugars and carbohydrates from the water extract of cotton lint. Recently Hendrix realized a considerable amount of research to better describe the insect honeydew using HPLC (chapter 4).

The procedure is the following: The water extract from the contaminated cotton is filtered with a 10 cm<sup>3</sup> syringe to which a 0.2 micron filter (nylon membrane-polypropylene housing) is attached. A 1.5-mL filtered sample is deposited into the 1.5-mL autosampler vial. Sugars are separated on the columns in series with a gradient eluent system: Eluent 1 is 200 mM sodium hydroxide and eluent 2 is 500 mM sodium acetate and 200 mM sodium hydroxide is used a pulsed amperometric detection system (Hendrix and Wei 1994). Using corresponding standards, the concentration of the sugar present in the extract is calculated from the area of the corresponding peak present in the chromatogram. The sugar content present on the lint could be expressed as a percentage of the fiber weight or as a percentage of the total sugar. A chromatogram of the standard sugars (inositol, trehalose, glucose, fructose, trehalulose, sucrose, turanose, melezitose, and maltose) used for the calibration is shown figure 1.

## Physical Tests

### Infrared Spectroscopy

Though several physical and chemical methods exist for the determination of stickiness levels in cotton, none have proven suitable for integration into a rapid classing protocol such as high volume instrument (HVI). The need to find a rapid, nondestructive, and

reliable test for the screening of potentially sticky cotton has led to the investigation of near infrared (NIR) spectroscopy as a possibility (Ghosh and Roy 1988, Taylor et al. 1994, Brushwood and Han 2000). Though some limited success has been achieved in developing calibrations of the NIR method with such measurements as the ferricyanide test for total reducing sugars, the NIR method does not, to date, provide a level of reliability to justify its use as a screening method for sticky cotton. The reason for this lack of success may lie partially in the fact that older scanning instruments do not achieve the resolution necessary to adequately discriminate glucose polymers (cellulose) from individual sugar moieties present on the surface of cotton. Newer Fourier-transform near infrared instruments provide an order of magnitude increase in resolution, which may be sufficient to provide the necessary discrimination.

### Stickiness Tester (Stanley Anthony Method)

Anthony first described this instrument in 1994. The apparatus essentially consisted of an infrared moisture sensor and a resistance moisture sensor. Indeed, preliminary research suggested that different types of measurements of moisture content such as resistance determinations, oven-drying, capacitance determinations, and near-infrared measurements yielded different estimates of moisture content as a function of the amount of sugars that were on the cotton. In cases where the natural sugar content was high, oven moisture determined by oven drying appeared to be elevated. In cases where the insect sugar content was high, the near infrared moisture was depressed. The resistance-based moisture meter was unaffected by the level of natural or insect sugar in the cotton.

From these observations, a new apparatus referred to as the “stickiness tester” was developed and patented. It combined measurements of resistance and infrared into one machine (Anthony et al. 1994, 1995, Anthony and Byler 1997). Anthony claims that this new device requires only a few seconds to predict the stickiness as compared to several minutes for the sticky cotton thermodetector. In addition, it also predicts the stickiness of seed cotton. This method is still under evaluation.

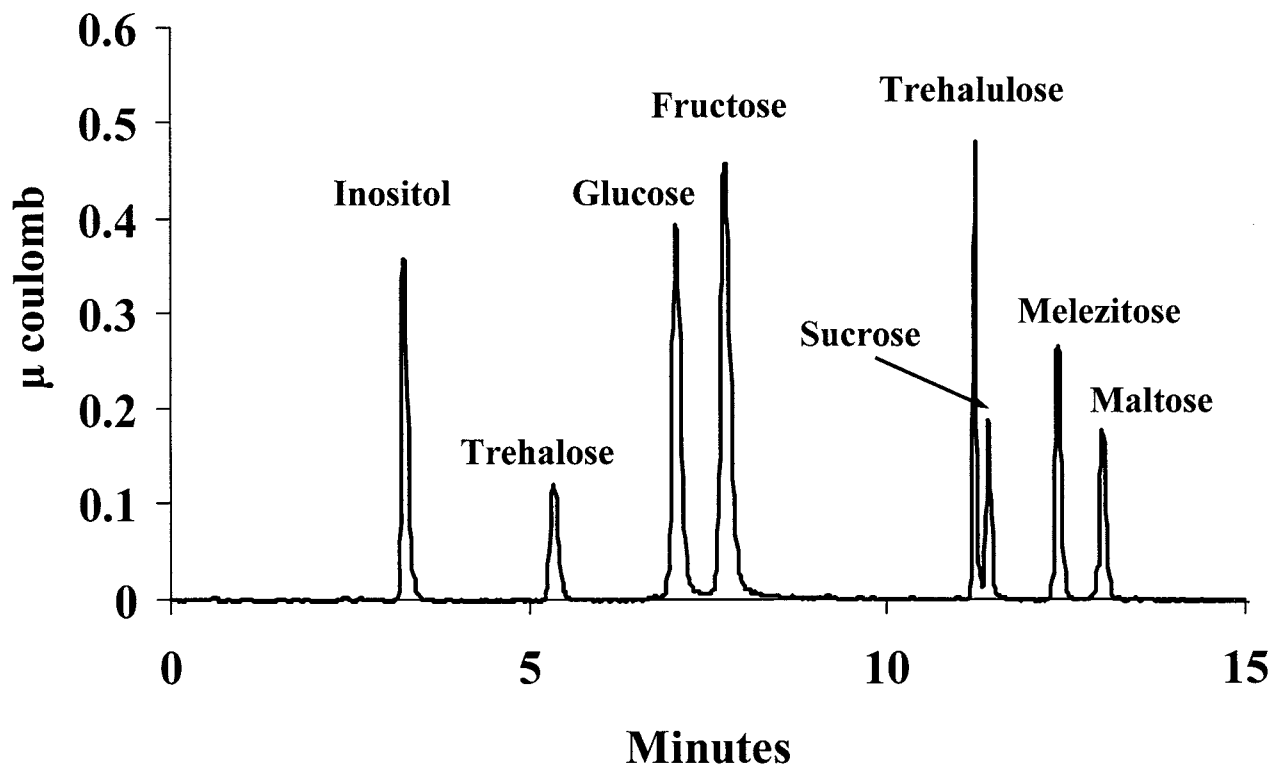


Figure 1. Chromatogram of the standard sugars used to calibrate the HPLC (1 = inositol, 2 = trehalose, 3 = glucose, 4 = fructose, 5 = trehalulose, 6 = sucrose, 7 = melezitose, 8 = maltose).

### Shenkar Stickiness Tester SST-1

The basic principle of this instrument, described by H. Bar-Yecheskel in 1992, is to mimic the textile process so that a sample of 60 to 80 grams of cotton is cycled around an apparatus that contains an opening and cleaning device followed by a pair of calender rolls. The calender rolls are continuously brushed to remove nonsticky deposits. At the end of the appropriate time interval, about 1 to 2 minutes, the cotton has made 15 to 18 cycles. The rolls are then removed from the machine and placed in a special scanning device where the sticky spots are measured for number and area. This method is still under evaluation.

### Quickspin Test

The basic principle of this instrument was described by P. Artzt (1998). The Quickspin is made of 2 modules. Module 1 consists of a MDTA3 (Micro Dust and Trash Analyzer 3) unit that opens the fiber sample to single fiber, cleans the sample, blends it, and finally

forms it into a sliver by means of a large rotor (1 meter perimeter). The second module is the rotor spin unit, which is fed from the sliver produced by module 1. Work on this method originated from the observation that, when using the Quickspin, it is sometimes difficult to remove the ring of fibers from the large rotor. It turned out that the reason for this problem was sticky deposits inside the rotor. From this observation a test method was developed which measures the weight of fibers sticking to the rotor as a percentage of the specimen weight. This method is still under evaluation.

### Minicard Test

The minicard test (figure 2) is a mechanical method for rating cotton stickiness based on processing the cotton through a miniature carding machine and assessing the degree of stickiness on the delivery rolls as the resulting web passes through. The rating system is based primarily on the tendency of the fiber web to wrap around the delivery rolls as a result of a sticky spot adhering to the rolls. Higher numbers of sticky

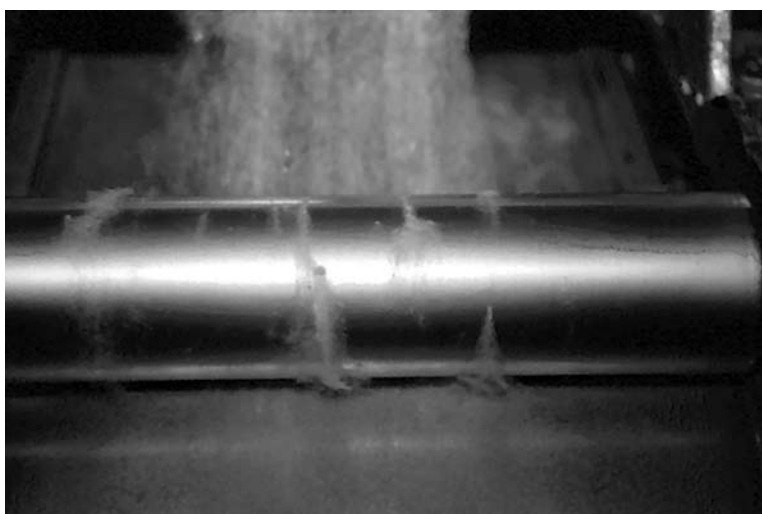


Figure 2. Contaminated crush roll of the minicard (picture: CIRAD).

spots on the web result in a higher number of wraps, and the cotton is then rated in one of four categories:

- 0 no stickiness
- 1 light stickiness
- 2 moderate stickiness
- 3 heavy stickiness

Requirements for performance of the test include maintaining the relative humidity between 55 and 65 percent and regularly cleaning the delivery rolls to prevent sugar buildup. The results of the minicard test are widely believed to correlate well with stickiness in the mill due to an essentially identical carding process, but the method is time-consuming and requires relatively expensive equipment. As a result, the method is used primarily as a reference method with which faster, simpler, and less expensive methods for measuring stickiness may be calibrated.

### Thermodetectors

#### Sticky Cotton Thermodetector (Manual)

The Sticky Cotton Thermodetector (SCT) (figure 3) was first described by R. Frydrych (1986). More recently CIRAD (2000b) proposed a standardization procedure. The author claims that the results obtained from this method are not directly related to the sugar content of the samples and that this method is valid only for stickiness caused by entomological sugars from insect infestations.

The general principle is the following: After conditioning the fiber samples for at least 12 hours, a specimen of  $2.5 \pm 0.05$  g is taken and opened (mechanical means are recommended) to form a web of  $540 \pm 20$  by  $160 \pm 20$  mm. The sample is then placed between 2 pieces of aluminum foil (dull face against the specimen) and the first pressure applied ( $780 \pm 50$  N for  $12 \pm 2$  seconds at  $84 \pm 4$  °C). A cold (room-temperature) pressure is applied immediately thereafter ( $590 \pm 50$  N on the preparation for  $120 \pm 10$  seconds).

Then, the preparation is left to rest for  $60 \pm 5$  minutes before counting the sticky points. To count the points, the upper piece of foil is removed carefully. Then, its surface is cleaned without applying too much pressure, and finally the points are counted. These operations are repeated for the lower piece of foil. The numbers of sticky points from the two pieces of foil for each specimen are summed. An average of three specimens per sample is recommended.

Operator effect is important with this technique.

The operator may have an influence on the sample preparation, the cleaning of the aluminum foil, and finally the counting.

#### High Speed Stickiness Detector (Automated)

Frydrych et al. (1994) first described the H2SD—high speed stickiness detector (automated version of the SCT)—in 1994. More recently CIRAD (2000a) proposed a standardization procedure. The limitations are the same as the ones found for the SCT: The results

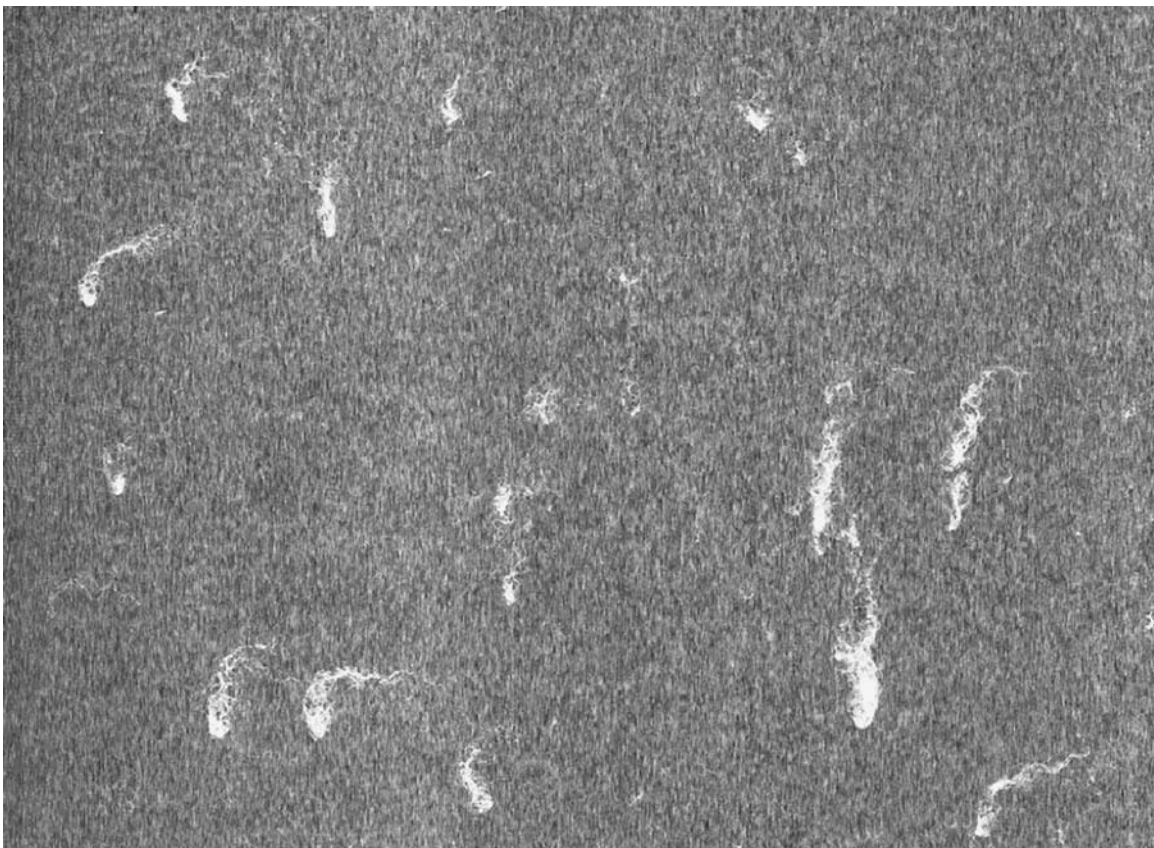


Figure 3. Sticky deposits on aluminum foil of the sticky cotton thermodetector.

obtained from this method are not directly related to the sugar content of the sample, and this method is valid only for stickiness caused by entomological sugars from insect infestations.

The general principle is the following: After conditioning the fiber samples for at least 12 hours, a specimen of  $3.25 \pm 0.25$  g is taken and fed into the instrument to be mechanically opened. It forms a pad of  $130 \pm 10$  by  $170 \pm 10$  mm. The sample is then automatically transferred to a strip of aluminum originating from a roll. The aluminum is rolled along a conveyor belt, which transfers the sample in front of each station. The aluminum strip is rolled up at the other end of the machine. The sample is transported to the first press where pressure is applied for  $25 \pm 2$  seconds while the heating element is in contact with the cotton. The heating element exerts a force of  $1,500 \pm 100$  N. The heating element's surface area is  $192 \text{ cm}^2$  (tolerance  $\pm 1 \text{ cm}^2$ ). Then, the sample is automatically transported to the second press where another pressure—the same amount as during the

hot-pressure phase—is applied for  $25 \pm 2$  seconds at ambient temperature. This fixes the sticky points to the aluminum foil. The sample is then transported to the cleaning station where the nonsticky material is removed by a combination of a cleaning roll and suction. The sticky point counting is made by image analysis.

The main disadvantage of the SCT, operator influence, is very limited with the H2SD.

Hequet and Abidi (2002b) selected 150 bales based on their insect sugar content. Those bales came from three different growing regions: one known to have important whitefly populations and very few aphids (area 1), one where both types of insects coexist (area 2), and one with large populations of aphids and very few whiteflies (area 3). The examination of the high-performance liquid chromatography results obtained on these bales revealed that all cottons were contaminated with insect honeydew to some degree. When expressed as a percentage of the total sugars the average trehalulose content for area 1 was 67 percent higher

than melezitose content, revealing whitefly honeydew contamination. For area 2, the average trehalulose content was 28 percent lower than melezitose content, revealing a probable contamination by whitefly and aphid honeydew. For area 3, the average trehalulose content was less than 2 percent of the melezitose content, revealing aphid honeydew contamination.

In order to establish the relationship between sugar properties and the high speed stickiness detector measurement, Hequet and Abidi (2002b) studied hygroscopic and thermal properties of the sugar present on contaminated lint. The authors have shown that the individual sugars present on sticky cotton have different hygroscopic properties (chapter 14). Among the sugars tested, trehalulose and fructose have the highest hygroscopicity. After equilibrium is reached, the amount of adsorbed water at 65 percent relative humidity and 21 °C corresponds to three molecules of H<sub>2</sub>O adsorbed per molecule of trehalulose or fructose. This suggests a relationship between water content of the raw material and stickiness. This confirms findings from previous work reporting that stickiness caused by honeydew depends on the relative humidity (Gutknecht et al. 1986, Frydrych et al. 1993).

Consequently, Hequet and Abidi (2002a) decided to test the samples at two different relative humidities. The lower level (55±2 percent) was selected to represent common ring spinning conditions. The higher level (65±2 percent) was selected to represent the standard textile laboratory atmosphere according to American Society for Testing and Materials Standard Practice D 1776 (ASTM 1990). Figure 4 shows a linear relationship between the high speed stickiness detector readings (square root transformed) performed at 55±2 percent relative humidity and 23±1 °C and readings at 65±2 percent relative humidity and 21±1 °C with the manufacturer-recommended hot plate temperature of the instrument set at 53 °C. The square root transformed H2SD readings at 55±2 percent relative humidity are on average 23.2 percent lower than at 65 percent relative humidity. No significant interaction between the area and the relative humidity was noticed. This suggests that the moisture absorption equilibrium of the sugars involved in the stickiness phenomenon is lower at 55 percent relative humidity than at 65 percent. Consequently, all the stickiness readings are lower, but it does not modify the relative ranking of the 3 areas.

Hequet and Abidi (2002b) showed that sugars present on honeydew-contaminated lint have different thermal properties. Among the sugars tested (inositol, trehalulose, glucose, fructose, trehalulose, sucrose, and melezitose), trehalulose exhibited the lowest melting point (48 °C). Therefore, when testing cotton for stickiness at 53 °C (manufacturer's recommended setting for the high speed stickiness detector), trehalulose, which is mainly present in whitefly honeydew, should melt while the other types of sugars should remain unchanged. As shown on the differential scanning calorimetry profile (figure 5), trehalulose begins to melt around 25 °C. Therefore, we can hypothesize that the honeydew droplets having a high percentage of trehalulose would be sticky at any temperature above 25 °C and that the lower the trehalulose percentage in those droplets, the lower the "sticky potential."

To confirm this hypothesis, the authors modified the H2SD hot plate to perform the stickiness measurement at different temperature settings. The following hot plate temperatures were chosen: 27 °C, 34 °C, 40 °C, 53 °C, and 67 °C. All of the tests were performed in standard laboratory conditions at 65±2 percent relative humidity and 21±1 °C. The results demonstrate that by testing at high temperature (67 °C), H2SD readings on the contaminated cottons are higher than at 53 °C with no significant interaction between area and temperature. However, at 27 °C significant interactions of area and temperature were noticed. H2SD readings at this temperature were lower: 46.4 percent for area 1 cotton, 54 percent for area 2 cotton, and 68.7 percent for area 3 cotton. This suggests that the origin of the contamination (whiteflies vs. aphids) may have an effect on the H2SD readings. Figure 6 shows H2SD readings for two types of cotton contaminated with honeydew from whiteflies and aphids. These two cottons had nearly the same number of sticky spots at 53 °C (72.8 and 71.7 spots respectively). However, when the hot plate temperature was lowered from 53 °C to 27 °C, the two cottons reacted differently. The cotton contaminated with whitefly honeydew remained sticky at lower temperature, whereas the cotton contaminated with aphid honeydew was not. Therefore, the question of the most appropriate hot plate temperature setting for the thermometers (SCT, H2SD, FCT) arises.

### **Fiber Contamination Tester**

The fiber contamination tester (FCT) was first described by Mor (1996). More recently, Lintronics

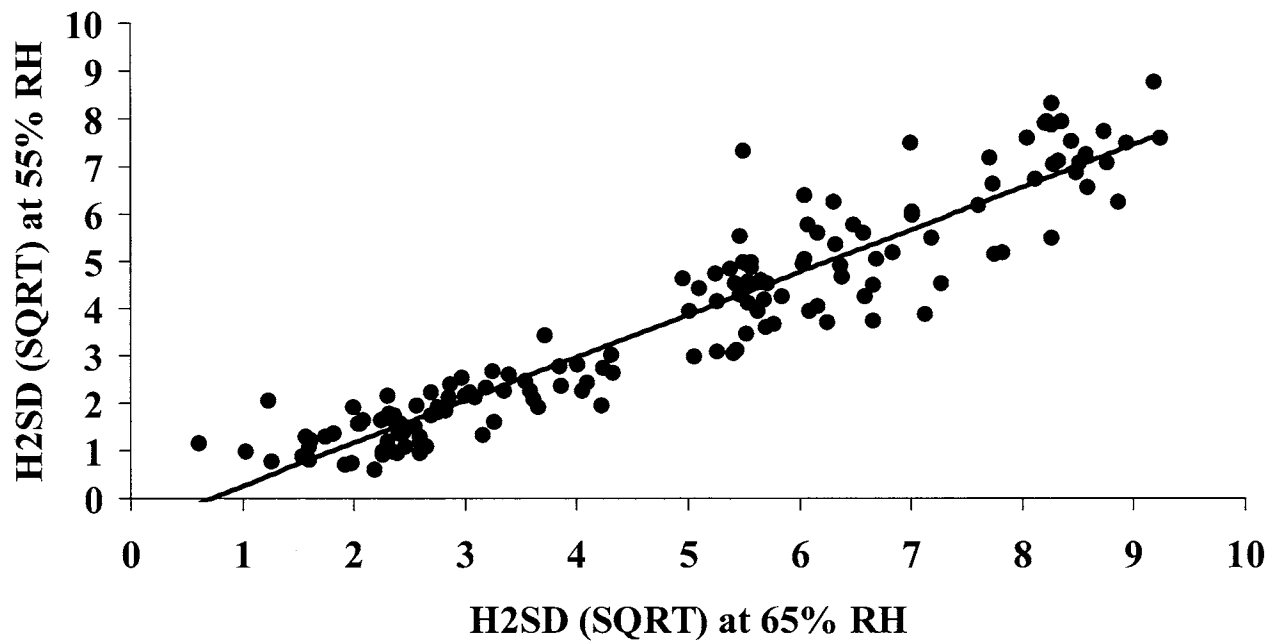


Figure 4. Relationship between H2SD reading at 65±2% relative humidity, 21±1 °C (square root transformed) and reading at 55±2% relative humidity, 23±1 °C (square root transformed) (Hequet and Abidi 2002a).

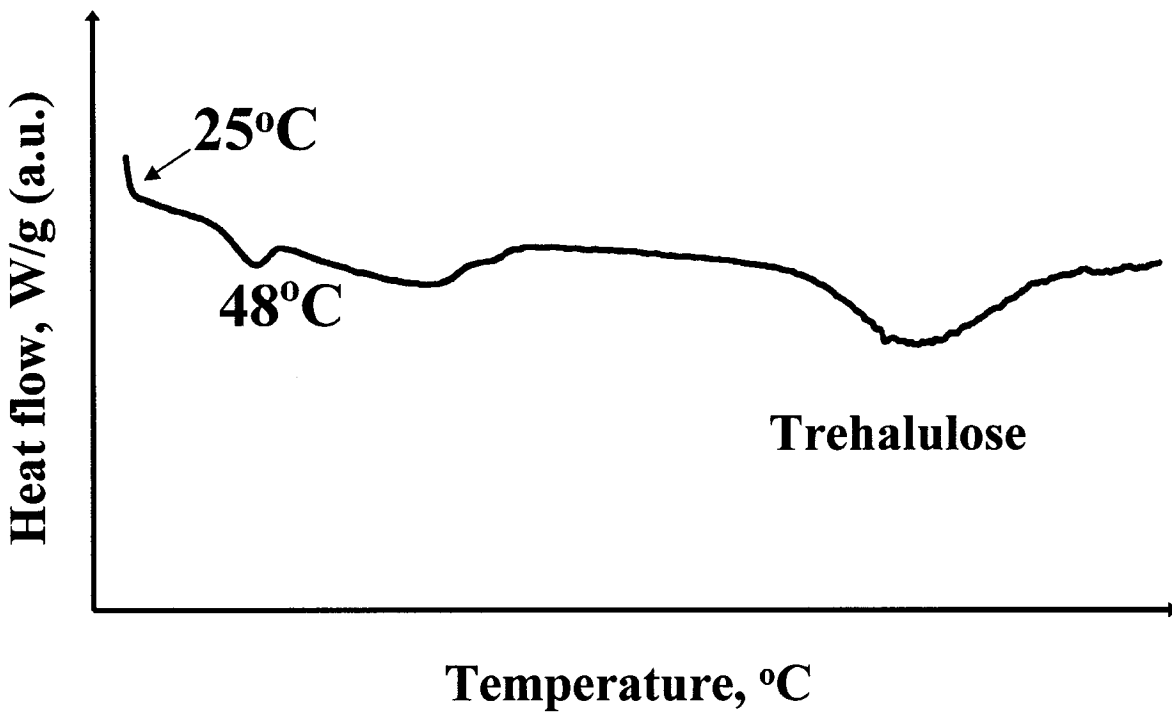


Figure 5. Differential scanning calorimetry profile of trehalulose (heat increase was 5 °C/min from 25 °C to 250 °C) (Hequet and Abidi 2002b). W/g = watts per gram; a.u. = arbitrary unit

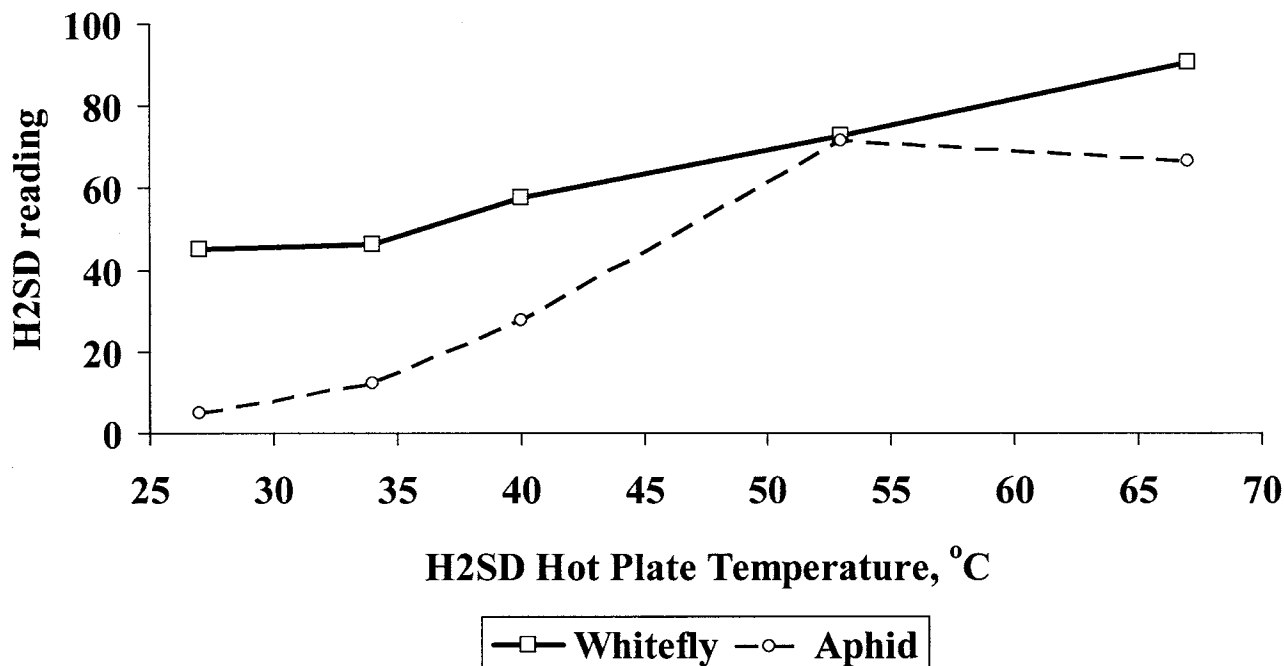


Figure 6. Effect of type of honeydew contamination on H2SD readings (Hequet and Abidi 2002a).

(2000) proposed a standardized procedure for this equipment. More claims that this instrument is able to detect stickiness from any origin (plant sugars, insect honeydew, oily substances, etc.).

The general principle is the following: A fiber sliver, whose mass and length is fixed, is fed into a microcard. The web formed passes between two drums under pressure. The sticky spots adhere to the drum where they are counted.

After conditioning the fiber samples for at least 12 hours, a specimen of 3.5 g is taken and shaped into a 30 cm long sliver. The sliver is placed on the feed belt of the instrument and automatically fed into the built-in microcard, which produces a thin web (analogous to the minicard web). The web then passes between two drums that are pressed by a constant pressure against each other. The sticky deposits adhere to the drums. Then the web is removed by a vacuum (constant suction) and discarded. While the drums are moving a laser optical system counts the number of events blocking the laser light. The accumulated amount divided by the sample weight determines the stickiness per gram.

Since the electronic signal that is generated by the laser corresponds to the amount of fibers, the size of every deposit is determined simultaneously. To prevent repeated detection of the same deposit, an aggressive cleaning (using brushes) is performed to clean both the fibers and the sticky materials from the drums. The friction applied by the brushes increases the drum temperature until it reaches a plateau. The signals collected from the optical sensors are then used to calculate the stickiness grade, which is a combination of the number of detected deposits and their size.

### Discussion

Among the reducing-sugar methods, the potassium ferricyanide, or Perkins, method has been one of the most widely used in the United States. In a very large experiment, Watson (1994) tested more than 2,000 samples of upland cotton lint from the 1993 U.S. crop. His conclusion was that reducing-sugar content is, at best, a poor estimate of fiber stickiness.

Since 1982 in Israel, the Cotton Production & Marketing Board has carried out systematic Follin tests (a variant of the Fehling test) on their crop during several years. Their conclusion was that the reducing-



sugar test was not satisfactory, since high sugar content has not always had an effect in the spinning mills (Peles 1992). Furthermore, Bar-Yecheskel et al. (1992) reported that there is no direct correlation between the percentage of sugar in cotton fibers and the severity of the stickiness phenomena in the mill. Through experiments conducted in the industry, they found that sometimes cottons having high sugar content did not manifest themselves as sticky in the mill, while cottons having low sugar content caused problems. They concluded that there is no obvious correlation between the results obtained by the reducing-sugar tests and cotton stickiness as experienced in the industry.

In fact, HPLC appears to be the only chemical method that is recognized by the research community. HPLC is an important research tool, providing us with important information about the source of stickiness (aphids, whiteflies, or physiological sugars). Nevertheless, this method is not intended for mass testing because it is time-consuming and costly.

Among the mechanical tests, the minicard test appears to relate quite well to spinning efficiency. Nevertheless, the instrument is not manufactured anymore, and it has some limitations. This is a slow test, and it is very difficult to clean off the honeydew spots from the flats and the cylinder teeth which can lead to contamination of subsequent samples.

The Shenkar tester, Quickspin, and stickiness tester (Stanley Anthony method) are still under evaluation, and not enough independent information is available to give an authoritative opinion.

SCT relates very well to the minicard (Gutknecht et al. 1988). This instrument is widely used around the world, especially in developing countries. Contamination of the instrument with honeydew has never been reported. Nevertheless, this is a slow and somewhat operator-influenced technology. SCT is not suitable for mass testing.

FCT and H2SD correlate very well and are able to provide reliable results (Hequet et al. 1998) at a speed close to HVI testing. Nevertheless the maintenance of the systems is a critical factor for the long-term stability of the results. In addition, calibration procedures as well as reference cottons need to be established.

Recent research (Hequet and Abidi 2002a,b) tends to demonstrate that neither the mechanical test nor

HPLC alone can provide reliable information about the processing problems at the mill (see chapter 14). It seems that both the sticky deposits information obtained by SCT, FCT, or H2SD and the individual sugar information (giving us the origin of the contamination, obtained by HPLC) are necessary to predict stickiness in the mill.

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## Chapter 14

### Fiber Processing

*E.F. Hequet, N. Abidi, M.D. Watson, and D.D. McAllister*

Cotton fiber quality determines the type of yarn and fabric that can be produced. Parameters such as fiber length, strength, and micronaire can be measured precisely and accurately with high volume instruments (HVI). These instruments, as well as the operating procedures associated with them, are well described and standardized. HVI data are used all over the world by the textile industry in buying cotton and in managing the mixes in the textile mills. Important, though not yet completely standardized, are measurement, characterization, and quality control standards for lint contaminants. In this chapter, we focus on one specific type of contaminant, cotton lint stickiness.

#### Effect of Stickiness on Productivity and Yarn Quality

Cotton stickiness caused by excess sugars on the lint, from the plant itself or from insects, is a very serious problem for the textile industry—cotton growers, ginners, and spinners (Hequet et al. 2000, Watson 2000). During the transformation process from fiber to yarn of sticky cottons—opening, carding, drawing, roving, and spinning—the machinery is contaminated to different degrees depending on the processes involved and the location within the machines. This affects processing efficiency as well as the quality of the products.

Stickiness is caused primarily by sugar deposits produced either by the cotton plant itself (physiological sugars) or feeding insects (entomological sugars) (Hendrix et al. 1995). Insects have been documented as the most common source of contamination in some studies (Sisman and Schenek 1984). The analysis of honeydew from cotton aphids (*Aphis gossypii* Glover) and sweetpotato whiteflies (*Bemisia tabaci* (Gennadius) strain B (= *Bemisia argentifolii* Bellows and Perring)) has shown that aphid honeydew contains around 38.3 percent melezitose plus 1.1 percent trehalulose, while whitefly honeydew contains 43.8 percent trehalulose plus 16.8 percent melezitose under the conditions described by Hendrix et al. (1992). Relative percentages may differ depending on environmental

or feeding conditions. Sucrose is virtually the only sugar in the phloem sap of cotton plants (Hendrix et al. 1992). The insects produce trehalulose and melezitose by isomerization and polymerization of sucrose. Neither of these sugars is produced by the cotton plant (Hendrix 1999); therefore, their presence on cotton lint demonstrates honeydew contamination. Furthermore, Miller et al. (1994) demonstrated that stickiness is related to the type of sugars present on the lint. The authors showed that trehalulose and sucrose, both disaccharides, were the stickiest sugars when added to clean cotton while melezitose (trisaccharide), glucose, and fructose (both monosaccharides) were relatively nonsticky.

Investigations have been conducted to elucidate the factors affecting the behavior of cotton contaminated with stickiness. In textile mills, the method mainly used to reduce the effects of stickiness is blending sticky cotton with nonsticky cotton (Perkins 1984, Hequet et al. 2000).

Gutknecht et al. (1986) reported that stickiness caused by honeydew depends on the relative humidity in which the contaminated cotton is processed. Relative humidity is a function of both water content and temperature of the air. Frydrych et al. (1993) reported that stickiness measured with the thermodetector is dependent on relative humidity. Price (1988) noticed that sticky cotton (with 1.2 percent reducing sugar content) when stored in high relative humidity (70 °F, 80 percent relative humidity) gave more problems during processing than the same sticky cotton stored at low relative humidity (75 °F, 55 percent relative humidity). However, at low relative humidity the fibers are more rigid, which will increase the friction forces creating static electricity (Morton and Hearle 1993). Therefore, milling machinery will require more energy to draw the lint.

Stickiness has also been reported to cause a buildup of residues on the textile machinery, which may result in irregularities or excessive yarn breakage (Hector and Hodgkinson 1989). When processing low to moderately contaminated cotton blends, residues will slowly build up. This translates into a decrease in productivity and quality forcing the spinner to increase the cleaning schedule.

Perkins (1983) reported that the cause of the severe stickiness of some 1977 California San Joaquin Valley cottons was probably whitefly honeydew. The

stickiness was most severe in the picking, carding, and roving processes, with frequent interruptions in production at carding and roving because of ends down and roll lapping. Storage of the cotton for more than 8 months did not relieve the stickiness. Processing the cotton through a tandem card eliminated the sticking problem at carding, but did not relieve the problem at roving enough to prevent production failures.

Fonteneau-Tamine et al. (2001a), studying 26 bales of Sudanese sticky cotton, reported that textile machinery performances decreased when sticky cottons were processed. At more than 50 sticky spots detected with the high speed stickiness detector (H2SD) and relative humidity between 45 and 50 percent during opening and carding, carding is not possible. In addition, stickiness reduces significantly the productivity well below the 50-H2SD-spot limit. As shown in table 1, the roving frame appeared to be the most sensitive of all the machineries involved in the fiber-to-yarn transformation.

Fonteneau-Tamine et al. (2001b) reported on the same lot of Sudanese cottons that cotton stickiness not only affects productivity but also the quality of the end products. Although a clear decrease in productivity was noted for both the carding and draw-frame operations, it did not translate into a measurable decrease in sliver quality. It is only from the roving frame onward that there is a stickiness-induced decrease in regularity. The coefficient of variation (as a percentage: CV%) of the roving mass is slightly higher, thus increasing the irregularity of the yarn on the ring spinning frame. When considering actual spinning, the quality of ring-spun yarn is more susceptible to stickiness than that of rotor-spun yarn. As shown in the table 2, the regularity, imperfections, and tensile properties clearly highlight this difference between the two processes. The CV% of mass, number of thin places, number of thick places, and number of neps in the ring-spun yarn increases significantly with the number of H2SD sticky points. The tensile properties of the ring-spun yarn decrease as stickiness increases. By contrast, most of the quality characteristics of the rotor spun yarn are unaffected by cotton stickiness.

Hequet et al. (2000) obtained very similar results. They examined the threshold level of stickiness for acceptable performances of both ring and rotor spinning, in terms of productivity and quality of the yarn produced. In the short term, between 0 and 11 sticky spots (average H2SD count of sticky spot in the

cotton mixes) the stickiness contamination does not appear to influence the productivity for either ring- or rotor-spun yarns, but it clearly does above this 11-spot threshold. Nevertheless, a slight but significant negative effect on the ring-spun yarn quality has been detected even at the very low levels of stickiness tested. No negative effect has been noticed on the quality of the rotor-spun yarn. In the long term, however, it appears that some insect sugars are slowly contaminating the equipment. This accumulation of sugars may reduce both productivity and yarn quality in the long term.

Stickiness may cause a buildup of residues on the textile machinery, which may result in irregularities or excessive yarn breakage. When the cotton is very sticky it cannot be processed through the card; however, with low to moderate stickiness levels, yarn can generally be produced. Hequet and Abidi (2002) studied the origin of the residues collected on the textile equipment after processing of sticky cotton blends with low to moderate levels of contamination. They worked with mixes having a very moderate level of stickiness in order to see, over time, a slow residue buildup on the textile equipment. This way of doing the spinning test is more representative of the industrial practice. Indeed, a spinner will not run a very, or even moderately, sticky blend. He will rather mix the sticky cotton in such a way that no short-term effect will be noticed. Nevertheless, in the long term, residues build up and translate into a slow decrease in productivity and quality, forcing the spinner to increase the cleaning schedule.

Twelve commercial bales contaminated with insect honeydew were selected based on their insect sugar (trehalulose and melezitose) content and their stickiness as measured with the high speed stickiness detector. In addition, five nonsticky bales from one module were purchased for mixing with the contaminated cotton so that alternative stickiness levels in the mixes could be obtained.

Preliminary tests were run on ring spinning before testing the mixes. Thirty pounds of lint from each bale was carded and drawn. If noticeable problems occurred at the draw frame, the process was stopped. If not, the drawing slivers were transformed into roving. If noticeable problems occurred at the roving frame, the process was stopped. If not, the roving was transformed into yarn at the ring-spinning frame. If noticeable problems occurred at the ring-spinning frame, the process was stopped. If not, 100 pounds of

lint was processed for the large-scale test. If noticeable problems occurred at any step of the process, the cotton was mixed with 50 percent nonsticky cotton and the process was repeated. Using this procedure led to the execution of 17 large-scale tests.

High performance liquid chromatography (HPLC) tests were then performed on card slivers, flat wastes, draw frame residues, and the sticky deposits collected at the end of each test on the rotor-spinning and ring-spinning frames. These tests quantify the amount of each sugar, expressed as a percentage of total sugars present. In addition, H2SD measurements were made on card slivers.

After each spinning test was completed, the opening line and the card were purged by processing a noncontaminated cotton, then all the equipment was washed with wet fabrics and thoroughly dried.

From the 12 contaminated and the 5 nonsticky bales, 17 mixes were evaluated in both ring and open-end spinning. As expected, H2SD readings on the mixes indicated slight to moderate stickiness (from 2.0 to 15.7 sticky spots). During the processing of the 17 mixes, sticky deposits were noticed on the textile equipment as shown in figures 1 to 3.

Figure 4 shows average HPLC results obtained on the 17 mixes for the fiber, the flat waste, and the residues collected on the draw frame and the drawing zone of the ring spinning frame. In this chart the HPLC results are normalized, the base being the HPLC results on the fiber. It shows that trehalulose content is always higher in the residues collected than on the original fiber while the other sugars are not. The same behavior was observed in rotor spinning (figure 5). Among the sugars identified in contaminated cotton, only trehalulose exhibits higher concentration in the residues.

Figures 6-10 show the nonlinear relationship between trehalulose on the fibers and trehalulose on the residues for some selected locations on the textile equipment. These figures show that during the processing of the mixes having trehalulose content above 5 percent of the total sugars, trehalulose content has a clear tendency to increase in the residues collected. Consequently, the authors decided to investigate the sugars' properties in order to understand why trehalulose content increases in the residues while the other sugars do not. The thermal properties of the five sugars identified on the contaminated fiber and on the residues collected on

the textile equipment were investigated. Differential scanning calorimetry was chosen to study the thermal properties of the following dehydrated sugars: fructose, glucose, trehalulose, sucrose, and melezitose. The differential scanning calorimetry profiles were recorded between 25 °C and 250 °C. Among the selected sugars, trehalulose has the lowest melting point (48 °C), as shown in table 3. It begins to melt immediately when the temperature starts rising. The other sugars remain stable when the temperature rises until it reaches 116 °C (melting point of fructose). Therefore, any increase in the temperature of the textile processing equipment will first affect trehalulose, causing it to either stick on the mechanical parts or become the precursor of nep formation. Figure 11 shows one example of a sticky nep collected from the yarn produced in this study.

Sugars belong to the carbohydrate class. They are hydrophilic because of several hydroxyl groups (-OH), which interact with water molecules, allowing many hydrogen bonds to be established. Therefore, several authors (Gutknecht et al. 1986, Price 1988, Frydrych et al. 1993) investigated the relationship between stickiness and relative humidity. It was generally reported that contaminated cottons are less sticky at low relative humidity than at high relative humidity. Therefore, the hygroscopic properties of the five sugars identified on the contaminated fiber were investigated. The quantity of water adsorbed on each sugar was evaluated at  $65 \pm 2$  percent relative humidity and  $21 \pm 1$  °C. Figure 12 shows the percentage weight gain during the first 12 hours of hydration. No sugar exhibited any significant variation within this time period except trehalulose, which picks up about 12 percent moisture; this corresponds to two molecules of water per molecule of trehalulose. Then, the weight gain of the sugar samples continued to be recorded until the plateaus were reached. Trehalulose continued to pick up moisture, while fructose began to pick up moisture after 12 hours of exposure to the laboratory conditions (figure 13). The hydration kinetic was very fast for trehalulose, with the equilibrium being reached after 80 hours, but slow for fructose, with the plateau being reached only after 500 hours. The total amount of weight gain corresponds to three molecules of water per molecule of trehalulose and three molecules of water per molecule of fructose. If we assume that trehalulose accumulates more on the spinning equipment than other sugars because of its hygroscopicity, then fructose should accumulate in a similar way, but this is not the case. Indeed, the HPLC tests performed on the residues collected on the



Figure 1. Sticky deposits on the draw frame creel drive rolls (Hequet and Abidi 2002).

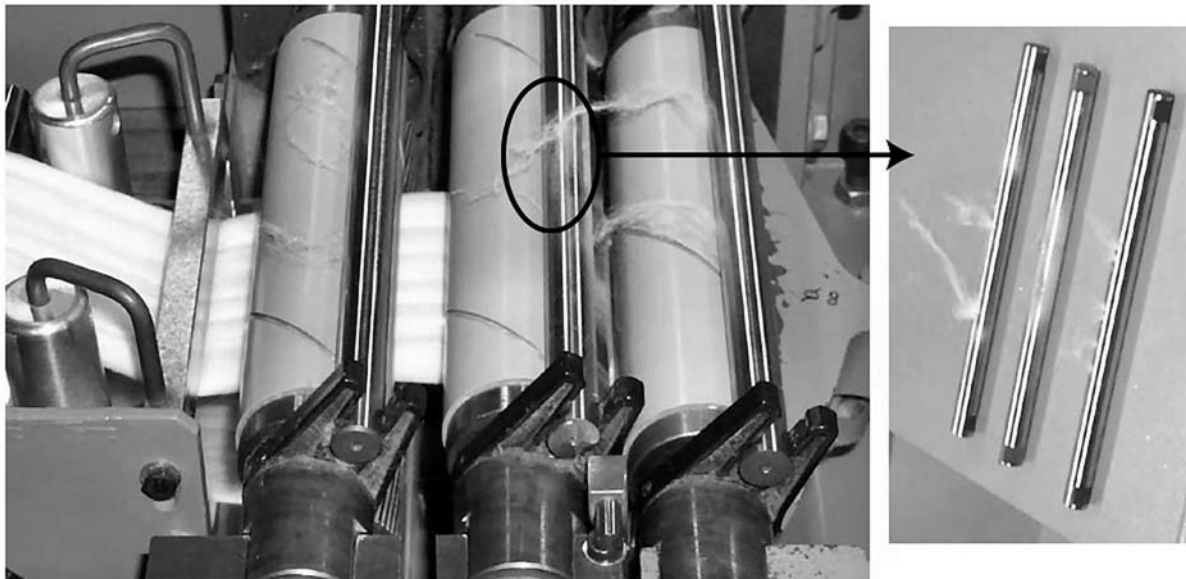


Figure 2. Sticky deposits on the drafting section of the draw frame (Hequet and Abidi 2002).

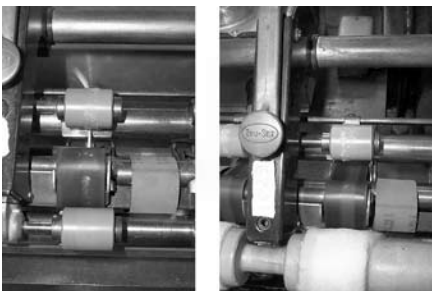


Figure 3. Sticky deposits on the ring spinning frame (Hequet and Abidi 2002).

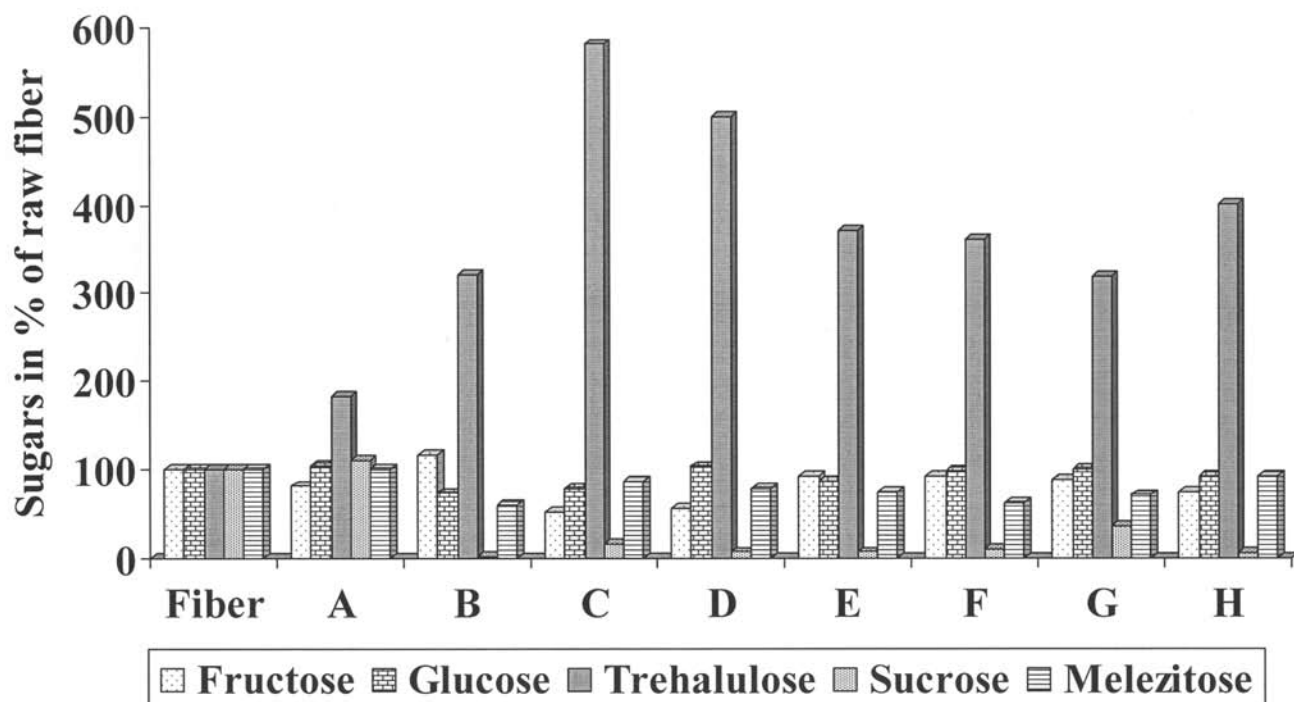


Figure 4. High performance liquid chromatography results on the 17 mixes for fiber, flat waste, and residues collected on the draw frame and the drawing zone of the ring spinning frame. The HPLC averages are normalized, base being the results on the fiber. A: card flat; B: draw frame, drafting zone; C: ring spinning frame, back rubber rolls; D: ring spinning frame, back steel rolls; E: ring spinning frame, belt; F: ring spinning frame, center rubber rolls; G: ring spinning frame, front rubber rolls; H: ring spinning frame, front steel rolls (Hequet and Abidi 2002).



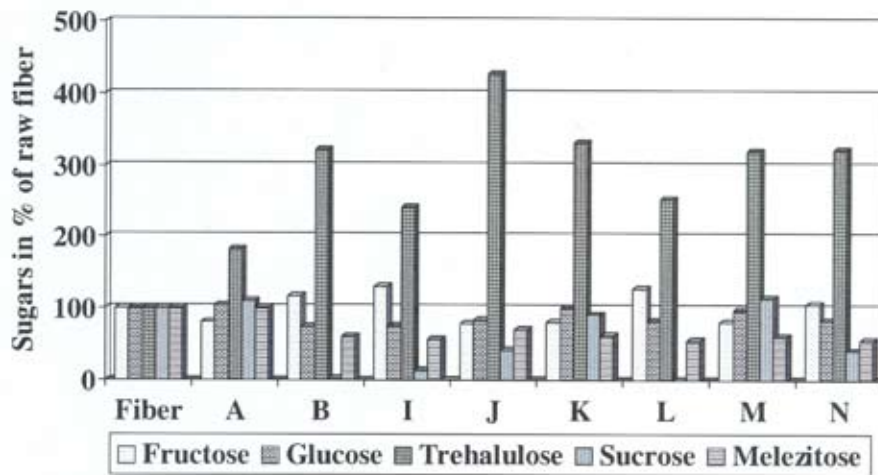


Figure 5. High performance liquid chromatography results on the 17 mixes for fiber, flat waste, and residues collected on the draw frame and the rotor spinning frame. The HPLC averages are normalized, the base being the results on the fiber. A: card flat; B: draw frame, drafting zone; I: rotor spinning frame, face plate; J: rotor spinning frame, feed table; K: rotor spinning frame, rotor groove; L: rotor spinning frame, rotor housing; M: rotor spinning frame, rotor ledge; N: dust test (Hequet and Abidi 2002).

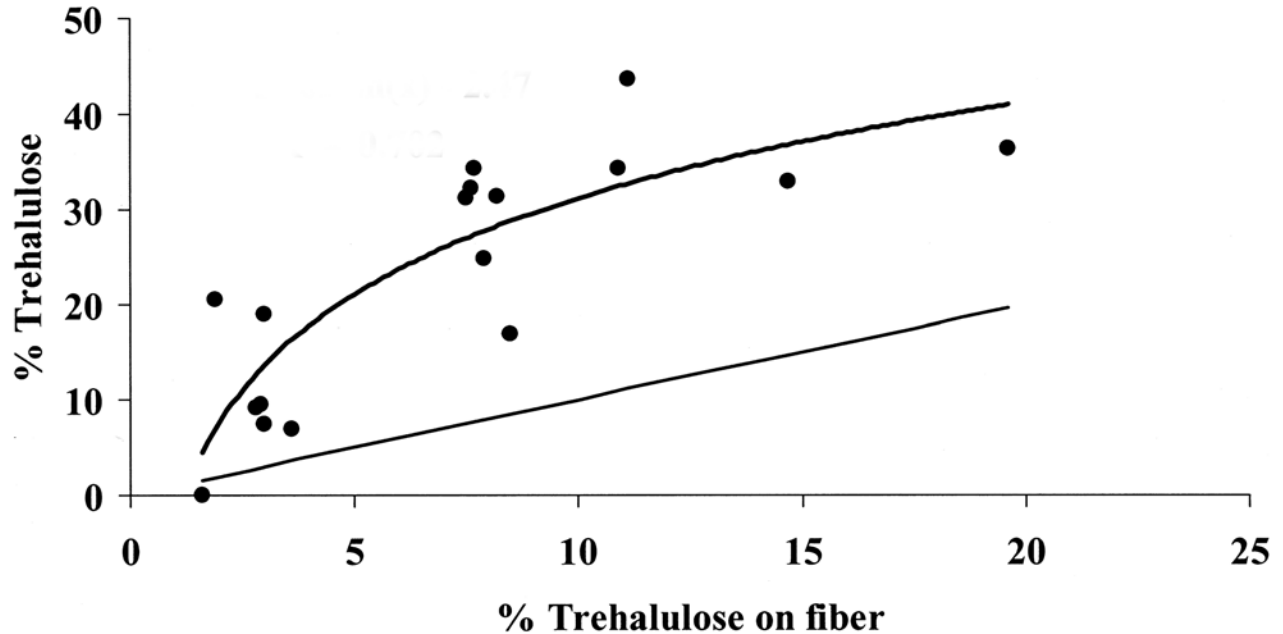


Figure 6. Relationship between the trehalulose content on the fiber of the 17 mixes and the trehalulose content on the residues collected from the front rubber rolls of the ring spinning frame. The trehalulose content is expressed as a percentage of the total sugars ( $y = 14.62\ln(x) - 2.47$ ;  $R^2 = 0.702$ ). The straight line is the equality line (Hequet and Abidi 2002).

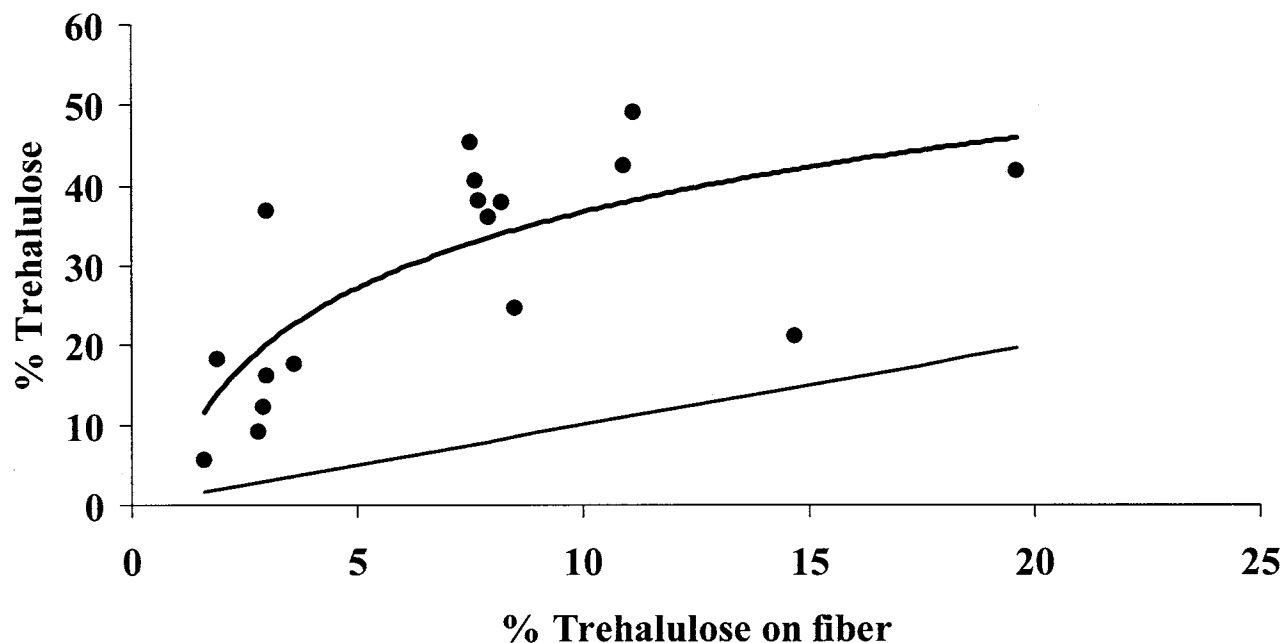


Figure 7. Relationship between the trehalulose content on the fiber of the 17 mixes and the trehalulose content on the residues collected from the front steel rolls of the ring spinning frame. The trehalulose content is expressed as percentage of total sugars ( $y = 13.78\text{Ln}(x) + 5.00$ ;  $R^2 = 0.527$ ). The straight line is the equality line (Hequet and Abidi 2002).

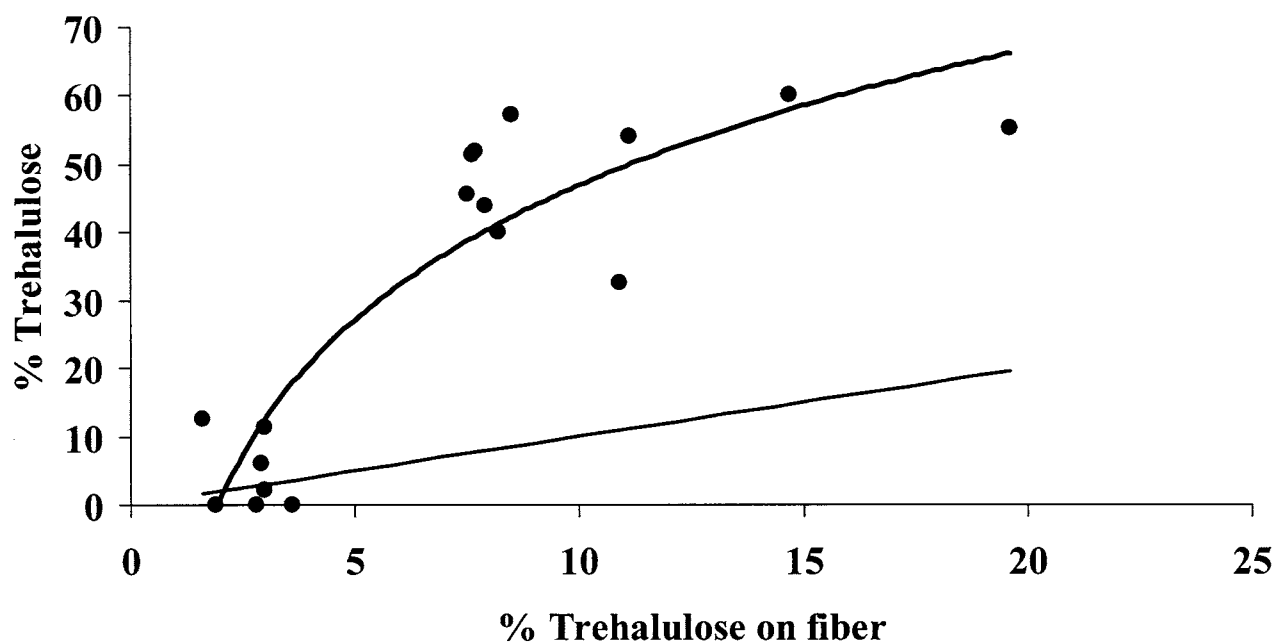


Figure 8. Relationship between the trehalulose content on the fiber of the 17 mixes and the trehalulose content on the residues collected from the rotor feed table of the rotor spinning frame. The trehalulose content is expressed as percentage of total sugars ( $y = 28.64\text{Ln}(x) - 18.98$ ;  $R^2 = 0.789$ ). The straight line is the equality line (Hequet and Abidi 2002).

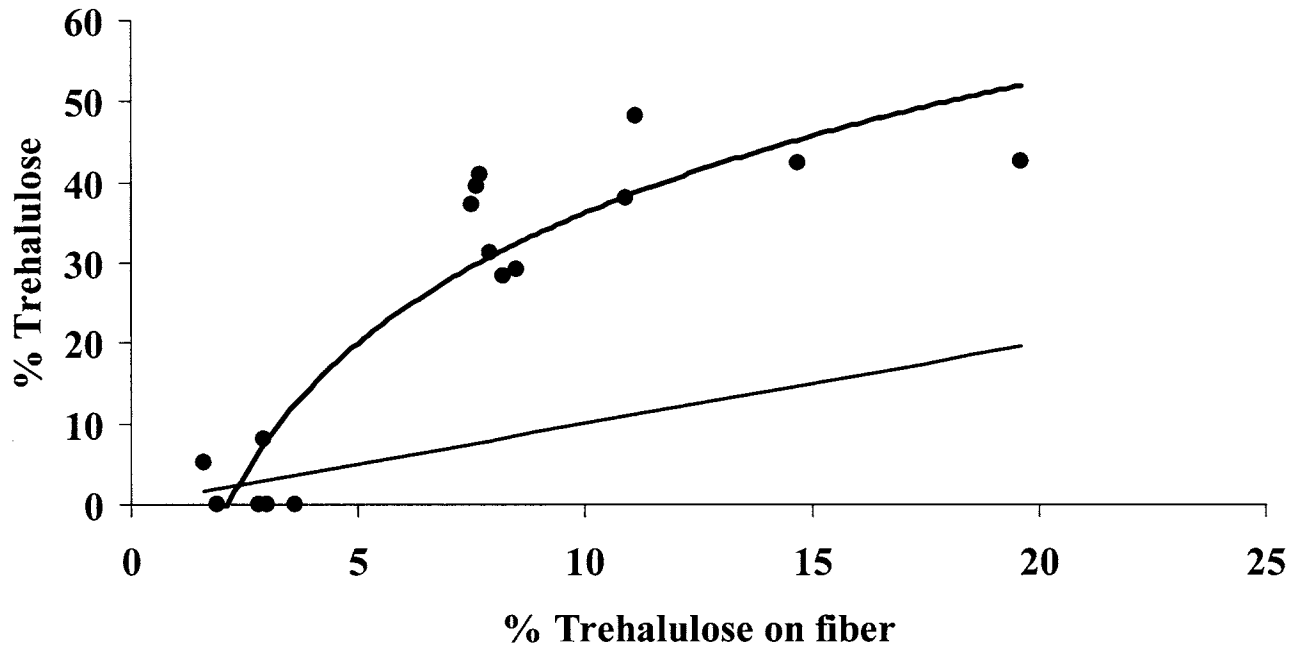


Figure 9. Relationship between the trehalulose content on the fiber of the 17 mixes and the trehalulose content on the residues collected from the rotor ledge of the rotor spinning frame. The trehalulose content is expressed as percentage of total sugars ( $y = 23.50\text{Ln}(x) - 17.97$ ;  $R^2 = 0.834$ ). The straight line is the equality line (Hequet and Abidi 2002).

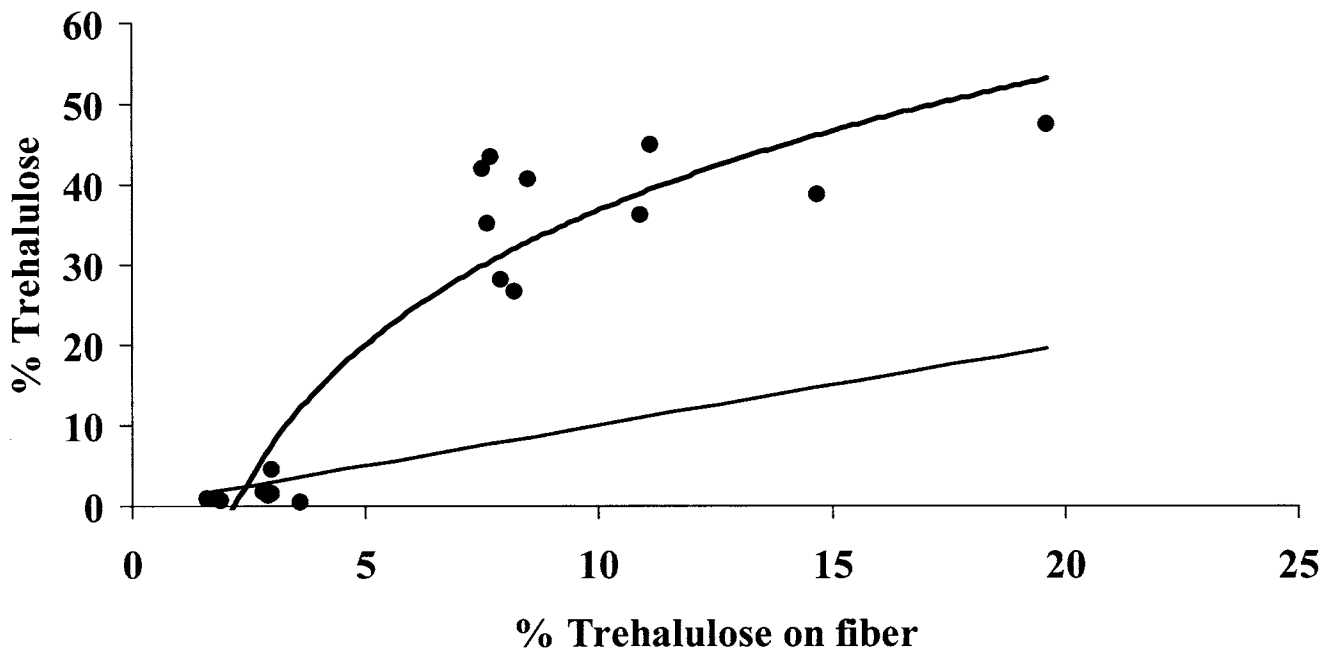


Figure 10. Relationship between the trehalulose content on the fiber of the 17 and the trehalulose content in the dusts collected from the dust tests. The trehalulose content is expressed as percentage of total sugars ( $y = 24.29\text{Ln}(x) - 19.10$ ;  $R^2 = 0.854$ ). The straight line is the equality line (Hequet and Abidi 2002).

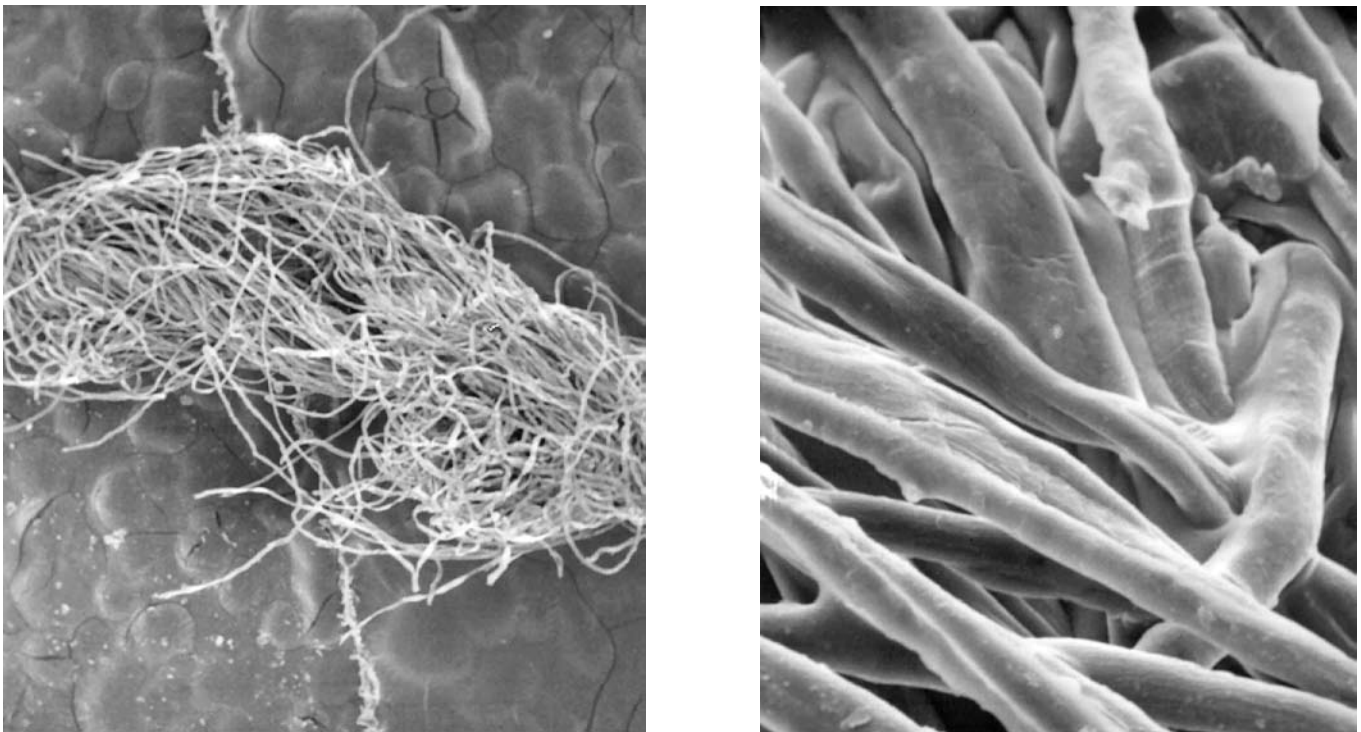


Figure 11. Scanning electron micrographs of a sticky nep (Hequet and Abidi 2002).

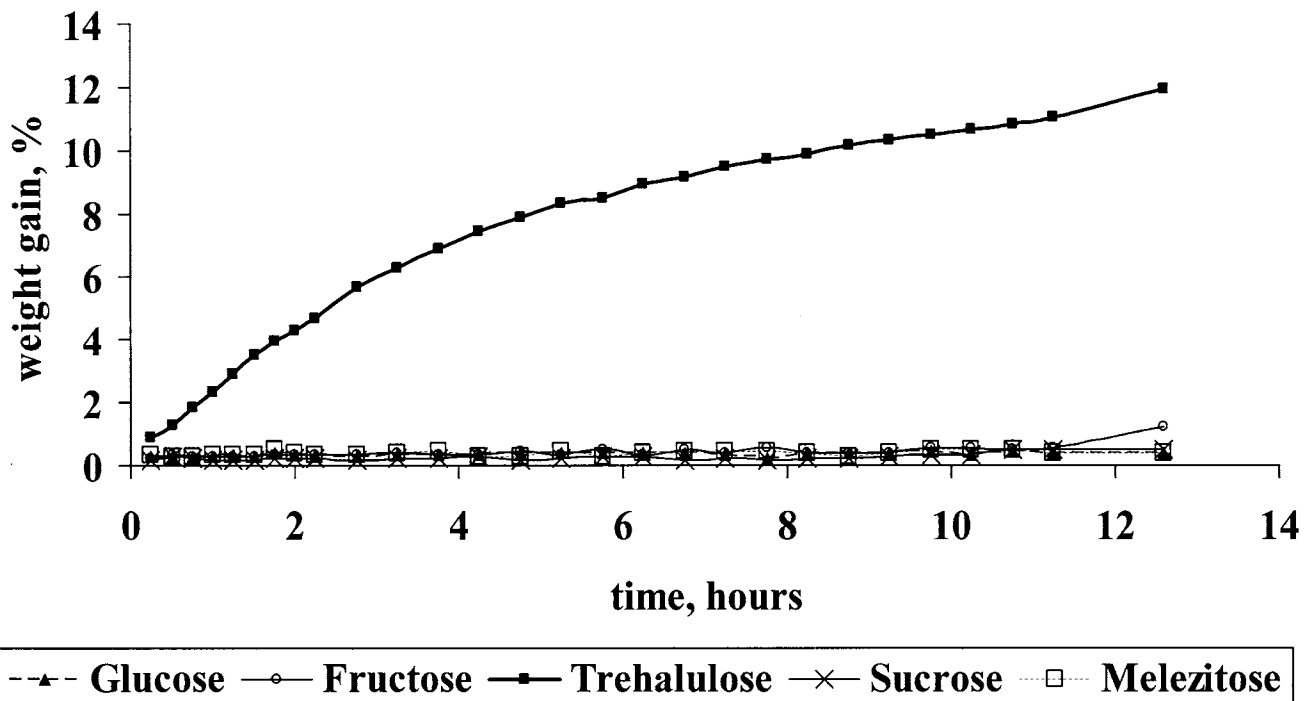


Figure 12. Hydration kinetic from 0 to 13 hours of selected sugars at  $65\pm 2\%$  relative humidity and  $21\pm 1$  °C (Hequet and Abidi 2002).

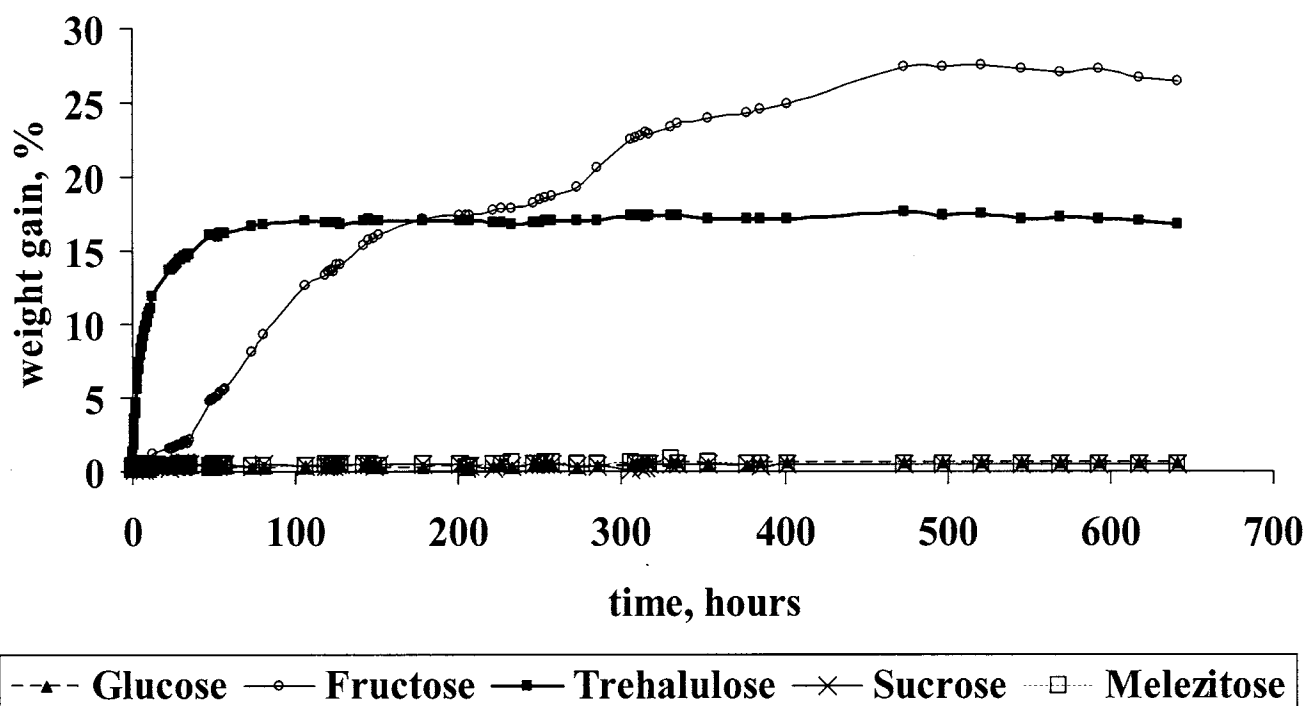


Figure 13. Hydration kinetic from 0 to 650 hours of selected sugars at  $65\pm 2\%$  relative humidity and  $21\pm 1\text{ }^\circ\text{C}$  (Hequet and Abidi 2002).

textile equipment do not show any increase in fructose content, even if fructose content was high on some mixes. On the 17 mixes tested, the fructose content, expressed as a percentage of the fiber weight, ranges from 0.012 to 0.101 percent, which corresponds to 10.6 to 33.6 percent when expressed in percentage of the total sugars identified. Thus, the fact that trehalulose is highly hygroscopic does not alone explain why this sugar has the tendency to accumulate more on the textile equipment than other sugars. The combination of high hygroscopicity and low melting point of trehalulose renders it stickier than the other sugars, allowing its higher concentration on the textile equipment.

The combination of high hygroscopicity and low melting point could explain the higher concentration of trehalulose in the residues collected on the textile equipment than on the original fiber. This research demonstrated that, among the sugars involved in cotton stickiness, trehalulose was probably the cause of the worst problems in processing. Thus, the effect of trehalulose throughout the spinning process was investigated for both conventional and compact ring spinning.

Hequet and Abidi (in press) processed 12 mixes, obtained by mixing sticky cotton with nonsticky cottons, through a short-staple spinning line. In addition to the trehalulose content (determined by HPLC), H2SD readings were obtained. The twelve mixes ranged from 0.013 percent to 0.204 percent of the fiber weight in trehalulose content and from 2.5 to 26.4 H2SD sticky spots. Among the mixes, some had high H2SD readings and low trehalulose content while others had high H2SD readings and high trehalulose content.

For this set of cottons, there was no correlation between H2SD readings and trehalulose content. Previous work done on 150 bales showed the same lack of correlation, especially in the low-to-moderate H2SD stickiness range. There was a marked evolution of the H2SD readings along the processing line and a strong interaction with the type of contaminant (aphid honeydew vs. sweetpotato whitefly honeydew), while there was only a slight evolution of the trehalulose content. It seems that some sticky spots, depending on the sugar composition, are broken into smaller particles in the opening line.

The mixes with high H2SD readings and low trehalulose content (aphid honeydew contamination) had no more ends down than mixes with low H2SD readings. Mixes with high H2SD readings and high trehalulose content (whitefly honeydew contamination) had excessive ends down or could not be processed. Cotton stickiness had a significant detrimental effect on both yarn evenness and yarn hairiness, even for the moderate levels of stickiness tested, but had no effect on yarn tenacity and CSP (count strength product).

In conclusion, stickiness affects productivity of the ring and rotor spinning processes and yarn quality. The origin of the honeydew contamination seems to affect the processability of sticky cottons. For a given level of stickiness, as measured by the H2SD, cottons contaminated with whitefly honeydew are more problematic to run in the spinning mill than cottons contaminated with aphid honeydew.

### **Effect of Storage on Stickiness**

Storage of cotton has been reported to either reduce or remove the incidence of stickiness. In other instances authors reported little to no effect of cotton storage on stickiness. Perkins (1986) reported that whitefly honeydew contaminated cotton samples were still sticky after 2 years of storage, while other sticky cotton samples with high physiological sugar contents were much less sticky after only 4 months of storage. Frydrych et al. (1993) reported that some spinners store sticky cottons with the hope that the natural decomposition of the sugars present on the lint will reduce stickiness. The authors concluded that, on the range of cottons contaminated with insect honeydew tested and after storage for more than 2 years under various relative humidity and temperature conditions, there was no significant change in cotton stickiness measured using the thermodetector.

It seems that stickiness from high level of physiological sugars may disappear after several months of storage because of biotic activities on the lint, while stickiness from insect honeydew will not. This could be due to the inability of most of the microorganisms to metabolize some insect sugars.

### **Effect of Mill Conditions**

In past publications, it has been suggested that machinery speeds, settings, roll pressures, and

humidity levels are likely to influence processing problems, namely roll lapping, caused by sticky cotton. In fact, many have provided data that show dry (low-humidity) conditions in processing areas of a textile mill will allow for the adequate processing of sticky contaminated cottons (Reynolds et. al. 1983, Perkins 1983, Gutknecht 1988, Price 1988). However, Backe (1996a) has suggested that (in addition to low humidity) bale bloom time, crush roll pressure, waste extraction, and cleaning cycles, either by themselves or in combination, can aid in alleviating the processing problems associated with sticky cotton.

Gutknecht (1988) has shown that the potential for stickiness increases for sticky contaminated cotton as the relative humidity of the surrounding atmosphere increases. Chellamani and Kanthimathinathan (1997) have reported that processing cottons known to be contaminated with stickiness at a relative humidity of 50 percent or lower will reduce the processing problems associated with these cottons. Backe (1996a) states that a relative humidity of less than 42 percent in the blowroom, carding, and drawing processes was helpful in processing sticky cotton. In addition, he indicates that success was met by allowing the bales to bloom in a fairly dry atmosphere for 48 hours prior to processing. Bringing the humidity surrounding the sticky contaminated cotton during processing to low levels dehydrates the sugars present on the sticky contaminated cottons. Hughes et. al. (1994) demonstrated that dehydrating the cotton to low levels of moisture drives off water until the sugar of the sticky contamination changes to a crystalline structure, which is not sticky. These researchers suggest that this effect seems to occur somewhere between 4.5 and 5.0 percent moisture content.

In processing sticky cotton, it was suggested by Backe (1996a) that relieving the crush roll pressure at the card will help in reducing the roll lapping on the crush rolls. However, Perkins (1993) warned that removing the crush roll pressure or increasing the gap between the crush rolls will allow large trash particles to remain in the stock, which could adversely affect yarn quality. Further, removing crush roll pressure to alleviate carding difficulties with sticky cotton will only act to transfer the problem downstream to drawing, roving, combing, and spinning. At these processes, roll lapping is a result of the sticky point on the cotton fiber attaching to the rollers in the drafting zone and subsequently collecting fiber passing through the zone. Known methods of minimizing this effect

are increasing the cleaning cycle of drafting rolls or treating the rolls with iodine to coat the rolls. Coating the rolls with iodine keeps the sticky point from adhering to the rollers and creating a roll lap (R. Insley, 2001, personal communication).

### Use of Additives

Since the 1980's, there have been many reports on the use of additives to process sticky cotton. Some success was demonstrated with nonionic combinations of hydrocarbon plus surfactant (Perkins 1983, 1984). However, Perkins (1971) warns that cationic additives will not be completely removed downstream in textile processing and will result in reduced scouring and dyeing efficiency. Chun and Brushwood (1998) have shown that treating cotton with water plus ammonia or urea at a 30 percent moisture content during storage for 15 days drastically reduced sugar content and stickiness without adverse affect on fiber properties. A practical application of these findings has not been developed.

Backe (1996b) reported on the use of a new additive, Gintex, for processing sticky cottons. This product is a nonoil- and nonsilicon-based product that is said to reduce fiber-to-machine friction so that fiber and foreign matter move freely without static electricity. In 1995, Backe (1996b) reported that several mills used this additive to process sticky cottons from the 1995 West Texas crop, Uzbekistan crop, and the crop from Francophone Africa with good success. Some of the positives of processing with this additive were said to be less dust, improved cleaning efficiency, increased yarn tensile properties, and improved mass evenness in addition to alleviating sticky cotton processing difficulties. Typically the additive is applied at the bale feeding (top feeder or hopper) stage of processing at the textile mill. Treating cottons with additives may be feasible if the user is willing to incur the additional cost for not only the additive but also the hardware to apply it.

**Table 1. Textile machinery efficiencies as a function of H2SD readings**

	Predictive equation	Coefficient of correlation
Card efficiency	$93.7 - 0.653 \text{ H2SD}$	-0.73
Drawing efficiency	$79.7 - 0.875 \text{ H2SD}$	-0.54
Roving efficiency	$100 - 13.88 (\text{H2SD})^{1/2}$	-0.76
Ends-down per 1,000 spindle hours	$-29.7 + 11.38 \text{ H2SD}$	+0.82
Open end efficiency	$98.3 - 0.134 \text{ H2SD}$	-0.66

**Table 2. Ring-spun and rotor-spun yarn (20 tex) quality as a function of H2SD readings**

	Ring-spun		Rotor-spun	
	Predictive equation	Coefficient of correlation	Predictive equation	Coefficient of correlation
CV%	$17.3 + 0.548 (H2SD)^{1/2}$	0.80		NS <sup>a</sup>
Thin places	$19.8 + 50.19 H2SD$	0.63		NS
Thick places	$653.8 + 15.13 H2SD$	0.82		NS
Neps (+200%)	$680.7 + 19.74 H2SD$	0.84		NS
Tenacity <sup>b</sup>	$3.75 - 0.0531 (H2SD)^{1/2}$	-0.57	$9.2 - 0.03 H2SD$	-0.55
Hairiness	$6.3 + 0.266 (H2SD)^{1/2}$	0.52	$5.2 + 0.107 (H2SD)^{1/2}$	0.48

<sup>a</sup> Nonsignificant.

<sup>b</sup> Square-root transformation.

**Table 3. Melting and decomposition points of selected sugars measured with differential scanning calorimetry**

Sugar	Melting point	Decomposition point
	----- °C -----	
Fructose	116	178
Glucose	152	210
Sucrose	184	215
Trehalulose	48	193
Melezitose	152	225

Source: Hequet and Abidi 2002



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## Chapter 15

### Overview, Conclusions, and Needs for Further Research

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Weaving plant fibers into cloth using hand-operated tools is documented in the earliest records of human civilizations (Scherer 1916, Smith and Cothren 1999). The evolution of mechanization in textile manufacturing has resulted in state-of-the-art, automated, high-speed cleaning, spinning, and weaving technology that meets the demand for high-volume, low-cost production but is vulnerable to malfunction from fiber contaminants and irregularities (Eliot et al. 1968). These tendencies to malfunction increased concern for fiber contamination of all types, especially those causing sticky cottonlint. Moreover, of all of the types of fiber contamination, stickiness is potentially the most costly for mills because stickiness is the only type of contamination with the potential to stop a production line in a very short time, sometimes within a few minutes.

#### Sources of Stickiness

Cotton lint contamination may originate from several different sources (Ellsworth et al. 1999), including mechanical adulterants, plant physiological sugars, and insect honeydew sugars. The presence of machinery lubricants or of high levels of certain types of plant trash may also cause sticking of lint in fiber processing (Hector and Hodkinson 1989; also see chapter 3).

Lint stickiness also has been associated with the presence of higher-than-typical levels of glucose, fructose, and sucrose in harvested cotton (chapter 3). Such elevated levels may occur when the latter part of the growing season is characterized by adverse growing conditions that delay maturity of a substantial portion of the bolls that make up the harvested crop. The most common environmental conditions that cause such delays in maturity are periods of cold temperatures during the weeks before crop termination and harvest (Hague 2000). In most instances, even after such events, rainfall before harvest leaches excess sugars from the cotton and stickiness is avoided. However, in rare events, physiological sugars may contribute to lint stickiness (Perkins 1971, Hague 2000).

Honeydew secretions from phloem-feeding insects are the major contributors to cotton lint stickiness problems worldwide (chapters 2 and 4). Much has been learned about stickiness, but additional information is needed before efficient, economical sampling, monitoring, detection, and amelioration systems can be developed.

#### Plant Physiological Sugars

Mature cotton lint often contains 0.25 percent or more reducing sugars of plant origin. Carter (1992) suggested that plant sugars may be as high as 0.75 percent in lint without causing stickiness. It has been hypothesized that because plant sugars are uniformly distributed over the fibers, the potential for stickiness is greatly reduced, assuming that the amount of such sugars is still below a critical level (Elsner et al. 1983, Bruno 1984). In fact the distribution of the plant sugars in or on fiber is unknown and cannot be ascertained directly by liquid extraction. Whether or not plant sugars are distributed uniformly, or if such uniform distribution would explain why low levels of physiological sugars (under 0.3 percent) do not cause fiber stickiness, remains in question. Others (Mor et al. 1982, Price 1988) have speculated that physiological sugars in some cases directly or indirectly contribute to lint stickiness. Nine individual naturally occurring sugars have been identified from extracts of clean cotton lint (Brushwood and Han 2000). Glucose, fructose, sucrose, and trehalose make up approximately 75 percent of the total physiological sugars present in lint, except when there is severe weathering or microbial damage. Smaller quantities of arabinose, arabitol, mannitol, mannose, and myo-inositol are also present. The exclusive contribution to lint stickiness of any individual sugar in a mixture of physiological sugars, is unknown and may be additive, synergistic, or antagonistic (Miller et al. 1994)

#### Insect Sugars

Honeydew on lint is droplets containing a concentrated mixture of sugars. The concentration and point-distribution of honeydew appears to contribute to the potential for sticking (Bourley et al. 1984, Hector and Hodkinson 1989). The evidence is irrefutable that most sticky cottons are associated with sugar deposits on lint that originate from insect honeydew contamination (Rimon 1982, Watson et al 1982, Sisman and Schenek 1984). Insects feeding on cotton phloem ingest a diet of sap that is high in sucrose. From this mainly sucrose source, sweetpotato whiteflies synthesize over two dozen sugars, mainly oligosaccharides (Hendrix and Wei 1994). The sugar components of honeydews from

cotton aphids, banded-winged whiteflies, and other insects that feed on cotton phloem are less well known.

The functions of the insect-synthesized sugars that are excreted as honeydew remain largely unknown. Some honeydew sugars very likely function to maintain osmotic balance and prevent insect water loss. Sweetpotato whiteflies metabolize simple carbohydrates to polyols that function as temperature stress mediators (Hendrix and Salvucci 1998, Salvucci et al. 1998, Wolfe et al. 1998). Further study of these biochemical processes would increase our understanding of insect physiology and plant-insect interactions and might lead to novel strategies for insect control. Development of feeding inhibitors or other mechanisms that could interfere, impede, or inhibit essential biochemical pathways in these pests may be attainable with the research technology available.

Insect-contaminated cottons characteristically contain trehalulose (a disaccharide) and melezitose (a trisaccharide) (Roberts et al. 1976, Byrne and Miller 1990, Hendrix et al. 1992, Brushwood and Perkins 1994). Thus, testing for trehalulose and melezitose is one means to identify cottons that have a high probability of sticking during processing. A number of higher molecular weight oligosaccharides are also found in honeydew and may contribute to stickiness (Hendrix et al. 1993, Brushwood and Perkins 1994, Hendrix and Wei 1994, Henneberry et al. 1998a,b). Sweetpotato whitefly contamination usually contains about twice as much trehalulose as melezitose. Trehalulose concentrations in cottons heavily contaminated with whitefly honeydew can easily exceed 30 percent of the total extracted sugars. Cotton aphid honeydew contamination contains little or no trehalulose, but melezitose levels may exceed 30 percent of total extracted sugars.

A simple, reproducible test to predict textile mill lint processing problems remains elusive (chapter 13). At present, for insect contaminated cottons, both a sticky spot determination (SCT, FCT, or H2SD) and HPLC identifications of the sugars are necessary to accurately predict the level of difficulty that may be encountered at the mill (see chapter 13). Physical tests measure number of spots, but the potential for stickiness is also determined by the composition of the sugars present. Trehalulose, the sugar characteristic of sweetpotato whiteflies, is much stickier than is melezitose, which is characteristic of cotton aphids (Miller et al. 1994). Thus, whitefly-contaminated cotton is much more

problematic than cotton-aphid-contaminated cotton if equal numbers of spots are indicated: It is necessary to know the source of contamination to interpret the results of physical stickiness tests.

Changes in weather, particularly rainfall, affect the amount of honeydew on lint in the field. Thus, sampling to monitor cotton stickiness potential in the field yields only time-specific results. Such considerations highlight the importance of defining where and when stickiness potential should be determined to allow maximum opportunity for preventative or remedial action.

## **Avoiding or Preventing Stickiness**

### **Insect management**

The most effective means to avert sticky cotton is the development and use of strategies that keep honeydew-producing insect populations and honeydew deposition below levels that result in stickiness. The numbers of sweetpotato whiteflies, cotton aphids, and possibly bandedwing whiteflies found on cotton plants are related to their honeydew production and the resulting potential for development of sticky cotton line (Henneberry et al. 1996, 1998a,b, 2000). Chemical control is the most common approach to reduction of honeydew-producing insect populations (Ellsworth et al. 1996b).

In the case of sweetpotato whiteflies, adult action treatment thresholds of 5 to 10 adults per leaf protect cotton yields and prevent honeydew contamination (Ellsworth and Meade 1994, Naranjo et al. 1998, Yee et al. 1996). These thresholds for conventional insecticides are conservative (Henneberry et al. 1995, 1996, Ellsworth et al. 1996a,b, 1997). Thresholds that include counts of adults and nymphs must be used for insect growth regulators (Ellsworth et al. 1996a, 1997). Counts of sweetpotato whitefly below approximately 9 adults per leaf turn and 3 nymphs per square centimeter of leaf disk have been associated with sticky cotton thermodetector counts of less than 5, a level associated with very low potential for sticking (Henneberry et al. 1998a,b,c). In Texas, Slosser et al. (2002) found that 11-50 aphids per leaf can cause sticky cotton. Thresholds are lower when plants are subject to low nitrogen and water stress. California cotton aphid thresholds are 10-15 cotton aphids per leaf following boll opening (Rosenheim et al. 1995, Godfrey et al. 2000).

Use of chemical control in combination with crop production techniques, cultural control methods, and insect resistance management is discussed in chapters 8, 9, and 12 and provide the guidelines for effectively managing sweetpotato whitefly and cotton aphid populations. Development of resistance to key insecticides is a continuing threat to effective chemical control with cotton aphids and sweetpotato whiteflies (Castle et al. 1999). Management systems that incorporate cultural, biological and behavioral control and host-plant resistance are essential for the future.

### **Crop Termination**

The possibility of producing sticky cotton confronts the grower with a number of difficult management decisions. Most cotton growers manage for high yields for the obvious economic consideration that high yields generally produce the highest profits. Another option is less often practiced. By reducing production costs, less-than-maximum yields are achieved, but profits may be as high as or higher than under management that uses high levels of inputs and attains maximum yields (Henneberry et al. 1998a,b). The decision to extend the growing season when sweetpotato whiteflies are present entails risks.

Under the growing conditions in the southwestern United States, in most growing seasons 95 percent of the upland cotton has already been produced by September 15 (Henneberry et al. 1998a,b). Extending the season without additional insecticide protection or additional rains allows sweetpotato whitefly populations to increase and increases the risk of stickiness. Accumulation of honeydew has been observed under research conditions: Clean lint became heavily contaminated over a period of 21 days (Henneberry et al. 1998a,b). These results suggest the benefits of early irrigation termination and defoliation. Incentives to avoid such a risk of sticky cotton also include direct savings in costs of additional water and insecticides. This research suggests that a formal economic analysis and risk assessment might be useful for growers who need to make these types of production decisions. For long-staple Pima cotton growers, mid-September termination probably involves an excessive loss of potential yield. Thus, the only economic option for Pima growers is to continue to treat the crop to maintain low sweetpotato whitefly populations.

### **Sampling and Testing for Stickiness**

The financial losses to textile mills and growers caused by sticky cotton are typically quite high (chapter 2). Without uniform prevention of stickiness in the field, through typically adequate insect control for instance, sticky cotton can be produced, ginned, and shipped to textile mills without being recognized until the bales are purchased and fiber processing begins. After a stickiness incident, discounts on lint grown in areas that have encountered stickiness may continue to penalize growers without justification unless there are reproducible sampling techniques, accurate testing procedures, and bona fide assurances that the newly produced lint is clean (Ellsworth et al. 1999). Recent economic history suggests that areas experiencing sporadic problems suffer persistent discounts for several years after the problem has been alleviated (chapter 2).

Since the earliest concerns about cotton lint stickiness, techniques for detecting, quantifying, and correcting lint stickiness have been researched. Some progress has been made. On the rare occasions when contamination is caused by lubricants, careful inspection of the lint can, in most case, result in identification of the source(s). Fructose, glucose, and sucrose make up the great majority of physiological sugars and may be extracted from cotton lint and readily quantified using chemical oxidation-reduction tests, enzymatic assays, and high performance liquid chromatography (chapter 13). Therefore, relatively simple and inexpensive methods are available for assessing contamination from mechanical sources or from plant sugars. However, the presence of excessive levels of physiological sugars in sufficient quantities to cause stickiness is a rare event (Hague 2000).

As stressed throughout this volume, most of the cotton lint stickiness problems throughout the world are caused by contamination with insect honeydews (chapter 4). Rapid identification and quantification of insect honeydew contamination is not simple, in part because the sugar components of insect honeydew are chemically complex. Honeydew-contaminated cottons contain plant sugars, but they also contain several other carbohydrates that are neither easily identified nor easily quantified (Hendrix et al. 1992, Hendrix and Wei 1994). At present, we lack rapid, inexpensive methods to measure stickiness potential in the field. Impediments to development of adequate field testing methods include the spatial and temporal variability of the contaminants, the chemical complexity of the

types of sugars that may be present, and the inherent differences in the stickiness potential of the individual sugars. Moreover, late-season weather conditions and conditions during harvesting, storage, and transport intervene between a postulated times of field sampling and the delivery of the cotton to the mill. In addition, preliminary evidence strongly suggests that the types of sugars present and their interaction affect their aggregate stickiness potential (Miller et al. 1994).

Physical methods that quantify lint contamination assess the overall stickiness potential of a sample, including both plant and insect sugars. The possible additive, antagonistic, and synergistic effects of several different sugars in a mixture are not well characterized. Moreover the insect sugars, being the most difficult and costly to quantify, are the most important causes of lint stickiness (Miller et al. 1994). The insect sugars that are found in the largest quantities in sweetpotato whitefly and cotton aphid honeydew are trehalulose and melezitose, respectively. Aphid and sweetpotato whitefly honeydews tend to produce similar counts as measured using the physical methods such as the SCT or H2SD but cause different levels of stickiness (chapter 13). Therefore in addition to a physical test methods (SCT, H2SD, or fiber contamination tester), a sugar analysis, such as HPLC analysis, must be used to estimate potential problems in lint processing. HPLC analyses are expensive and must be interpreted by chemists or experienced technicians. Physical testing provides counts that may be correlated with fiber processing performance, but unless the identity of the sugars are known, stickiness potential cannot be predicted accurately. In effect, if the textile mill does not know if the counts represent plant, aphid, or sweetpotato whitefly sugars, or some estimated combination of these sources, the processor can not accurately predict the degree of stickiness that may be encountered. More rapid, economical, and simpler methodologies of measuring lint stickiness are needed for practical use by the industry.

Development of statistically valid methods for sampling lint for stickiness potential in the field, module, or bale is fraught with difficulties (chapter 12). The potential for the contamination of lint with insect honeydews begins with cotton boll opening. Sampling during the latter stages of crop development might assist growers to determine if insecticide use would be economically justified. Use of chemical control can effectively reduce insect numbers but is expensive. If insect populations continue to increase,

treatments should be continued during the period when mature bolls are open and the lint is exposed. However, in retrospect, treatment might be unnecessary if rain subsequently falls before harvest.

Possibilities for removing honeydew from bolls in the field are limited. Overhead irrigation may have potential for reducing lint stickiness (chapter 13). Positive results have been achieved in some studies in Israel and in Texas, but results in California were not promising. However, the promising results suggest an opportunity to develop a system that might provide more consistent results.

### **Postharvest Considerations**

Limited information is available on the effects of harvesting, module storage, ginning and lint cleaning, and bale storage on honeydew-contaminated cotton and its potential for stickiness when it reaches the textile mill. Lack of such information hinders efforts to identify points in the cotton production and processing system where sticky cotton sampling and quality control standards could be advantageously employed.

Storage of cotton has been reported to either reduce or remove the incidence of stickiness. In other instances, authors reported little to no effect of cotton storage on stickiness potential. Perkins (1986) reported that cotton samples contaminated by whitefly honeydew were still sticky after 2 years of storage, while cotton samples with high physiological sugar contents were much less sticky after only 4 months of storage. Frydrych et al. (1993) reported that some spinners store sticky cottons with the hope that the natural decomposition of the sugars present on the lint will reduce the stickiness potential. The authors concluded that, on the range of cottons contaminated with insect honeydew tested and after storage for more than 2 years under various conditions of relative humidity and temperature, there was no significant change in cotton stickiness measured using the thermodetector.

It seems that stickiness caused by high levels of physiological sugars may disappear after several months of storage due to biotic activities on the lint, while stickiness from insect honeydew will not. This could be due to the inability of most of the microorganisms to metabolize some insect sugars.

In past publications, it has been suggested that machinery speed, settings, roll pressure, and humidity level are likely to influence processing problems,

namely roll lapping, caused by sticky cotton. In fact, many have provided data showing that dry conditions (low humidity) in processing areas of a textile mill will allow for the adequate processing of sticky contaminated cottons (Perkins 1983, Reynolds et al. 1983, Gutknecht 1988, Price 1988). Gutknecht (1988) has shown that the potential for stickiness increases as the relative humidity of the surrounding atmosphere increases. Chellamani and Kanthimathinathan (1997) have reported that processing cottons known to be contaminated with stickiness at a relative humidity of 50 percent or lower will reduce the processing problems associated with these cottons.

## Conclusions

Cotton stickiness caused by excess sugars on the lint, from the plant itself or from insects, is a very serious problem that affects all segments of the cotton industry. Stickiness is a worldwide contamination problem: Around one-fifth of the world production is affected to some degree. Stickiness is essentially caused by sugar deposits produced either by the cotton plant itself or by feeding insects, with the latter known to be the most common and serious source of contamination. The sugar composition of water extracts from honeydew-contaminated cottons analyzed by HPLC is extremely complex. Among the identifiable sugars, the disaccharide trehalulose and the trisaccharide melezitose are specific to insects and are not found in the plant. In general, a high percentage of melezitose along with a low percentage of trehalulose reveals the presence of cotton aphid honeydew, whereas both melezitose and trehalulose present with trehalulose dominant indicates sweetpotato whitefly honeydew contamination.

Insect populations are not uniformly distributed within a field, and neither are their excreta. A large within-sample variability and an even larger within-bale or -module variability is expected. Therefore, when testing for stickiness the problem of sampling is of the utmost importance. Our overall conclusions regarding commercial feasibility of stickiness classification is that, regardless of whether samples are collected from modules or bales, stickiness of ginned lint is simply too variable to achieve reasonable precision with only a single or a few sample units, especially when stickiness levels are between 0 and 10 H2SD spots. Nevertheless, precise stickiness evaluation in a laboratory is achievable when using multiple samples per bale and an adequate number of replications.

It has been demonstrated that the high hygroscopicity, low melting point, film-like structure, and high adhesiveness of trehalulose affect stickiness measurement with thermomechanical methods (Hequet and Abidi 2002). Based on these properties, trehalulose is expected to be the main source of concern in textile processing. Specifically, we can anticipate a selective accumulation of trehalulose on the textile equipment along with lower productivity and yarn quality.

Spinning experiments confirmed that among the identified sugars present on the contaminated lint only trehalulose accumulates on the equipment. It slowly contaminates the machinery—first sticking to surfaces, then catching dust, silica, etc. This contamination can increase the friction forces within the machinery and lead to excessive wear and temperature increase. This accumulation of sugars could have a negative effect on both productivity and yarn quality over the long term. It might also suggest that the threshold level between problems and no problems at the textile mill level could be different for whitefly-honeydew-contaminated cotton and aphid-honeydew-contaminated cotton. Recently, spinning experiments showed that cotton mixes that are moderately contaminated with aphid honeydew (around 26 H2SD sticky spots) can be processed with no major detrimental effects, while cotton mixes even slightly contaminated with whitefly honeydew cannot be processed without major detrimental effects, especially when ring-spun (Hequet 2003). Therefore, we cannot apply a single threshold limit for acceptable stickiness at the textile mill level. We need at least two threshold limits, one for aphid-contaminated cottons and one for whitefly-contaminated cottons.

## Research Progress

Although considerable knowledge has been developed through the sticky cotton research conducted over the last two decades, the problem remains a serious concern annually or sporadically in many cotton production areas of the world (chapter 2). The Honeydew Working Group of the International Textile Manufacturer's Federation was established in 1980 (Hector and Hodkinson 1989) to identify methods of stickiness detection, to determine the role and contribution of plant and honeydew sugars to lint stickiness, and to identify solutions to the problem. Methods to identify plant and entomological sugars have been developed that are reliable and reproducible (chapter 13). Additionally, thermodetector

measurements correlate with plant sugars, insect sugars, and insect populations (chapter 5 and 12). Thermodetector methods have been accepted as the international standard for lint stickiness measurement.

## Research Needs

### Plant Sugars

Little work has been done to measure the baseline concentrations of sugars that are found in the mature lint of contemporary cotton cultivars grown under current management conditions. Similarly, little is known about the quantitative effects of managing a crop for early vs. late maturity or the effects of harvest aids, harvest timing, or freezing. Preliminary evidence suggests that early harvest does not increase the probability of stickiness, but that harvesting following a freeze may predispose cotton to stickiness (Hague 2000).

### Management of Phloem-Feeding Insects

The first line of defense in prevention of sticky cotton is adequate control of the phloem-feeding homopteran insects—the cotton aphid and the sweetpotato whitefly. Since the 1970s the increase in stickiness as an international problem in textile processing has been strongly associated with the expansion of sweetpotato whiteflies as a serious pest. Over this period, sweetpotato whiteflies have become a major pest of cotton in Sudan, Israel, Francophone Africa, Pakistan, Central Asia, the western United States, Mexico, the Caribbean Basin, and Australia. Management of aphids and whiteflies depends on cultural practices that reduce susceptibility of the crop to the pests, monitoring the movement and reproduction of the pests in the crop, and use of timely and economically effective chemical control measures. Both cotton aphids and whiteflies have demonstrated a penchant for development of resistance to insecticides (Castle et al. 1999). Thus, resistance management principles must be integrated into the overall management programs for each of these pests or the risk of early loss of modes of insecticide action will be increased (Ellsworth et al. 1996a). Additional research on the biology, physiology, and interaction of aphids and whiteflies with the cotton plant may be expected to provide useful information for development of management strategies.

### Stickiness Detection and Quantification

Much needs to be learned about the properties of the individual sugars and mixtures of sugars and the interaction of plant and entomological sugars.

Standardized procedures for detection of stickiness potential in the field and estimation at the module, at the gin, in storage, in shipping, and at the mill remains a formidable research challenge.

## Processing

We have seen that there are important differences between types of honeydew. Their chemical compositions differ, and the hygroscopic and thermal properties of the sugars involved are different. These differences affect stickiness measurement with thermomechanical methods and should logically affect fiber processing. Limited spinning experiments have confirmed this. Nevertheless, more work needs to be done to determine the effect of the type of stickiness contamination on—

- the cleanability of stickiness by mechanical devices such as the opening line and the card in the textile mills,
- the effect of stickiness on modern textile equipment (high-speed carding, compact spinning, high-speed rotor spinning, air-jet spinning, vortex spinning, combing, etc.), and
- the effect of sticky yarn (yarn produced from moderately sticky cottons) on knitting and weaving efficiency as well as fabric quality.

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## Glossary

### Selected Terms Associated With Sticky Cotton and Cotton Production and Processing

**Abiotic:** Inorganic, not living

**Acala cotton:** Type of upland cotton that originated in the Acala Valley, Mexico.

**Alate:** Having wings or winglike parts.

**Aldehyde:** A carbon atom double-bonded to an oxygen (carbonyl group), single-bonded to a hydrogen, and single-bonded to another chemical group.

**American egyptian cotton:** Original name for extralong-staple cotton in the United States.

**Anion:** Negatively charged ion.

**Anomeric:** Refers to stereoisomers (compounds that have the same kinds and numbers of atoms but have different molecular arrangements) of a sugar which differ only in how they are configured about their respective carbonyl (anomeric) carbon atom.

**ANOVA:** Analysis of variance. A statistical technique that analyzes the contribution to an experimental result made by independent variables

**Anthesis:** Flower blooming period, pollen shed.

**Aphid:** Any of several species of sap-sucking, soft-bodied insects (order Homoptera) about the size of a pinhead, with tubelike projections on the abdomen. The cotton aphid, *Aphis gossypii* Glover, is of specific focus in cotton lint contamination.

**Bale:** Package of compressed raw cotton weighing about 480 pounds. The most common bale dimensions are 55 in. long, 20-21 in. wide and 26-30 in. thick.

**Bale sample:** Cotton fiber samples from a bale on each of two sides, each weighing at least 4 oz. from each of two sides. For American pima cotton, sample weight is at least 5 oz. a piece.

**Bandedwinged whitefly:** (*Trialeurodes abutiloneus* Haldeman) A whitefly species; adults have visible

wide, gray bands on their wings and piercing-sucking mouthparts that enables feeding in plant phloem tissue.

**Bifenthrin:** A synthetic pyrethroid ester insecticide and acaricide.

**Biotic:** Pertaining to life, caused by living organisms.

**Carbamate:** A salt or an ester of carbamic acid, especially one used as an insecticide.

**Carbofuran:** A cholinesterase inhibitor that is used as a systemic insecticide, acaricide, and nematocide.

**Carbohydrate:** Any member of a very abundant class of natural organic substances composed of carbon, oxygen, and hydrogen. Among other compounds, this class includes sugars, starches, and cellulose.

**Carding:** Process of separating, cleaning, and aligning textile fibers and forming them into a continuous, untwisted strand called sliver.

**Cellulose:** Polysaccharide consisting of 3,000 or more D-glucose units linked together in the  $\beta$ -1-4 conformation.

**Chitin:** Nitrogenous compound found in arthropod body covering.

**Chlorpyrifos:** An organothiophosphate cholinesterase inhibitor that is used as an insecticide and acaricide.

**Color grade:** In cotton classing, a combination of the degree of brightness or dullness and the degree of yellowness of the cotton as judged by the visual appearance.

**Combing:** A processing step before carding to straighten fibers and extract foreign matter and short fibers.

**Contaminant:** Substance that contaminates; substance that pollutes. Contaminants causing stickiness comprise various types of foreign matter found on the lint such as honeydew or plant sugars.

**Cotton aphid:** (*Aphis gossypii* Glover) Aphid species that attacks cotton.

**Cotton classing:** System of estimating the quality of cotton in a bale by measured fiber properties compared to standards.

**Cotton fiber maturity:** The relative degree of development of the secondary wall of cotton fibers.

**Cotton gin:** The principal function of a cotton gin is to separate lint from seed, but the gin must also be equipped to remove foreign matter, moisture, and other contaminants that significantly reduce the value of the ginned lint.

**Cotton grade:** An established degree of quality based on visual appearance such as color grade or leaf grade.

**Cotton leaf curl:** Virus-caused cotton plant disease.

**Cotton lint stickiness:** *see* Stickiness.

**Crop termination:** Stopping active crop growth using chemicals to prepare for harvest.

**Crush rolls:** Pair of smooth pressure rolls positioned after the doffer in a cotton card to disintegrate remaining vegetable trash in the card web.

**Cultivar:** A strain or genotype that is, or was, available for commercial production.

**Cutout:** Period in mid-season cotton crop phenology when flowering temporality ceases.

**Cyhalothrin:** A synthetic pyrethroid ester insecticide and acaricide.

**Defoliant:** Chemical applied to cotton plants to cause their leaves to drop off prematurely, facilitating harvesting.

**Desiccant:** Chemical substance that absorbs moisture. Such compounds are commonly used as cotton defoliant.

**Dicrotophos:** Organophosphate insecticide.

**Disaccharide:** Substance that is composed of two molecules of simple sugars linked together.

**Drawing:** The process of increasing the length per unit weight of laps, slivers, or roving.

**Economic injury level:** Pest injury level at which control is cost-effective.

**Economic insect threshold:** Pest density that indicates need for management action to prevent increase to density that causes economic injury.

**Ecosystem:** An ecological community within a physical system.

**Egyptian cotton:** Extralong-staple cotton, *G. barbadense*, developed in Egypt.

**Endosulfan:** A synthetic highly toxic crystalline insecticide.

**Endotoxin:** A toxin produced by certain bacteria and released upon destruction of the bacterial cell.

**Ends-down:** A condition in which one or more ends have broken in a textile machine.

**Entomological sugars:** Sugars present in insect honeydew, such as melezitose and trehalulose.

**Enzyme:** A catalytic protein that changes the role of specific biochemical reaction.

**Epicenter:** A focal point

**Epidermal:** Outer layer of cells.

**Epizootic:** Epidemic among animals of a single kind within a particular region.

**Ethephon:** A synthetic plant growth regulator that induces flowering and abscission by promoting the release of ethylene. Ethephon has been used to cause early ripening of apples.

**Extrafloral:** Not associated with the flower; outside the flower.

**FCT:** Fiber contamination tester, an instrument that is able to test for stickiness, among other fiber properties. The general principle is the following: A fiber sliver, whose mass and length is fixed, is fed into a microcard. The web formed passes between two drums under pressure. The sticky spots adhere to the drum, where they are counted.

**Fecundity:** Progeny production capability.

**Fiber:** Thin strand of cotton.

**Fiber contamination tester:** *see* FCT.

**Fiber processing:** Process of transforming an unorganized mass of fiber into yarn and fabric.

**Filter chambers (in insects):** Chamber in the gut of homoptera that excretes excess water, sugar, waste, and honeydew.

**Fructose:** A very sweet monosaccharide sugar,  $C_6H_{12}O_6$ , that occurs in many fruits and honey.

**Genotype:** Genetic components of an organism.

**Ginning:** Action of separating cotton fibers from the seed.

**Gin stand:** A functioning belt system component of a cotton gin that feeds seed cotton into the seed extraction device and separates fibers from seed.

**Glucose:** Monosaccharide that is the main source of energy in the cell.

**Gossypium:** Scientific name for the cotton genus.

**Grader sample:** A sample of at least 4 ounces (115 grams) taken from each side of a bale by a licensed sampling agent for USDA cotton classification.

**Gradient HPLC:** High performance liquid chromatography method in which eluant composition varies during analysis.

**Gram-negative bacteria:** Bacteria that, following treatment with gentian violet dye and iodine, and safranin counterstained, appear bright pink to red.

**Growth regulator:** A chemical that controls physiological processes within a plant.

**Gut lumen:** Entomology term describing the cavity in the intestine of an insect.

**H2SD:** High speed stickiness detector, an instrument that detects cotton stickiness. Following pressure, a heating element fixes sticky spots to the aluminum foil and is measured by image analysis.

**Hemolymph:** The circulatory fluid of certain invertebrates, analogous to blood in arthropods and to lymph in other invertebrates.

**Herbicide:** Chemical used to kill or inhibit the growth of unwanted plants in the fields.

**High speed stickiness detector:** *see* H2SD.

**Honeydew:** A sticky, sugary substance that is produced by some types of insect and that may be deposited on plant parts.

**HPLC:** High performance liquid chromatography. *see* Gradient HPLC; Isocratic HPLC.

**HVI:** High volume instrumentation for cotton quality measurements of length, strength, and micronaire.

**Hydrolyze:** To react with water, as a chemical compound.

**Imidacloprid:** A systemic insecticide chemically related to the tobacco toxin nicotine. Like nicotine, it acts on the nervous system.

**Immature cotton:** Cotton lint from bolls not fully mature.

**Insect growth regulator:** Any chemical that mediates insect growth, molting, maturation, or metabolism.

**Insect honeydew:** *see* Honeydew.

**Insect sugars:** Sugars present in honeydew that are not from plant origin, such as trehalulose or melezitose.

**Instar:** An insect or other arthropod between molts.

**Ion:** Electrically charged particle.

**Isocratic HPLC:** High performance liquid chromatography using a constant-composition mobile phase.

**Isomer:** A compound that exists in forms having different arrangements of atoms but the same molecular weight. Any of two or more substances that are composed of the same elements in the same proportions but differ in properties because of differences in the arrangement of atoms are called isomers.

**Ketone:** Any of a class of organic compounds, such as acetone, having a carbonyl group linked to a carbon atom in each of two hydrocarbon radicals and having the general formula  $R(CO)R'$ , where R may be the same as  $R'$ .

**Laps:** Sheets of fiber formation.

**Laydown:** Selection of bales for processing at the textile mill (also referred to as mixing).

**Leaf turn:** Terminology from sweetpotato whitefly sampling to describe turning cotton leaves over to count adults in the field.

**Leaf water potential:** A common physiological measurement used to assess the general water status of a plant. A value of zero indicates the absence of water stress, while increasingly negative values depict increasing severity of water stress.

**Lint cleaner:** Machine for removing foreign matter from lint cotton.

**Long staple:** *Gossypium barbadense* cotton with long fibers compared to upland cotton.

**Lumen:** The continuous canal that runs longitudinally in each cotton fiber.

**Malpighian tubule:** One of a system of tubules for waste disposal in insects that filter the body fluid (hemolymph) and dispose of the filtrate via the alimentary canal (functionally analogous to vertebrate kidneys).

**Melezitose:** Trisaccharide found in both whitefly and aphid honeydew. It is built from two molecules of glucose and one molecule of fructose.

**Methomyl:** An insecticide.

**Microflora:** The part of the plant population consisting of individuals that are too small to be clearly distinguished without the use of a microscope. Includes algae, bacteria, and fungi.

**Micronaire:** A characteristic determined by both fiber fineness and maturity. An airflow instrument is used to measure the air permeability of a constant mass of cotton fiber compressed to a fixed volume.

**Middling:** Cotton classing term, usually the middle grade of a series of grades.

**Minicard:** The minicard test is a mechanical method for rating cotton stickiness based on processing the cotton through a miniature carding machine and assessing the degree of stickiness on the delivery rolls as the resulting web passes through. The rating system is based primarily on the tendency of the fiber web to wrap around the delivery rolls as a result of a sticky spot adhering to the rolls.

**Mitochondria:** Component of living cells having enzymes.

**Module:** A stack of seed cotton normally containing 12-14 bales of picked cotton or 8-10 bales of stripped cotton.

**Module averaging:** Averaging, on a voluntary basis, of HVI measurements of micronaire, strength, length, and length uniformity.

**Molecule:** The smallest grouping of atoms which exhibit all the chemical characteristics of a substance.

**Molting:** Shedding of outer covering in insects.

**Monosaccharide:** Any of several carbohydrates, such as tetroses, pentoses, and hexoses, that cannot be broken down to simpler sugars by hydrolysis. Also called simple sugar.

**Morph:** Variant type.

**Nectary:** A glandlike organ, located outside or within a flower, that secretes nectar.

**Nymph:** Immature stage between egg and adult insect.

**Okra leaf:** Cotton with deeply lobed leaves as opposed to the standard leaf shape.

**Oligosaccharide:** A carbohydrate that consists of more than two monosaccharides.

**Organophosphate:** Any of several organic compounds containing phosphorus, some of which are used as fertilizers and pesticides.

**Osmolarity:** The concentration of an osmotic solution especially when measured in osmols (a standard unit of osmotic pressure based on a one molal concentration of an ion in a solution) or milliosmols per liter of solution.

**Osmoregulation:** Maintenance of an optimal, constant osmotic pressure in the body of a living organism.

**Osmotic:** of or relating to osmosis.

**Osmosis:** Diffusion of molecules through a semipermeable membrane from a place of higher concentration to a place of lower concentration until the concentration on both sides is equal.

**Diffusion:** The intermingling of molecules in gases and liquids as a result of random thermal agitation.

**Overwintering:** Term used to describe the stage of an insect that survives the winter to actively reinfest cotton in the spring.

**Oviposition:** The depositing of eggs, especially by insects.

**Paradigm:** An example or pattern.

**Paraquat:** Cotton harvest aid, a dessicant used in cotton defoliation.

**Parasitoid:** Any of various insects, such as the ichneumon fly, whose larvae are parasites that eventually kill their hosts.

**Pedicel:** The stalk of an insect egg.

**Phenology:** The scientific study of periodic biological phenomena, such as flowering, breeding, and migration, in relation to climatic conditions.

**Phloem:** The food-conducting tissue of vascular plants, consisting of sieve tubes, fibers, parenchyma, and sclereids. Also called bast.

**Phloem sap:** Material that flows in plant phloem.

**Physiological sugars:** Simple sugars in cotton fiber derived from the plant; mainly glucose, fructose, and sucrose.

**Pima cotton:** *Gossypium barbadense*, long-staple cotton.

**Plant growth regulator:** Agricultural chemical that affects plant growth.

**Plant sugars:** Carbohydrates synthesized by the cotton plant as a routine part of its metabolism (*see* Physiological sugars).

**Plant trash:** Plant and leaf material in lint, which is extracted at various lint-cleaning stages.

**Poisson distribution:** Statistical term describing the distribution of discrete variables in which the mean equals the variance.

**Postsynaptic:** Occurring after a nerve impulse.

**Pymetrozine:** Pyridine azomethene chemical insecticide.

**Pyrethroid:** Any of several synthetic compounds similar to pyrethrin; used as insecticide.

**Reducing sugars:** Sugars such as glucose or fructose in which the anomeric carbon is free (not bonded to another group) to act as a ketone or aldehyde.

**Relative humidity:** A measure of the dryness or dampness of air; the part or fraction of invisible water, in the form of vapor, actually present in air as compared with the maximum moisture the air can hold at a given temperature and atmospheric pressure. Expressed as a percentage.

**Ring spinning:** A system of spinning using a ring and traveler take-up wherein the drafting of the roving and the twisting and winding of the yarn onto the bobbin proceeds simultaneously and continuously.

**Roller gin:** Either of two types of gin. One consists of a leather ginning-roller, a stationary knife held tightly against the roller, and a reciprocating knife that pulls the cotton seed from the lint as the lint is held by the roller and the stationary knife. The second type uses a rotary knife instead of a reciprocating knife.

**Rotor spinning:** The creation of yarn by transferring twist from the end of a previously formed yarn to fibers or clumps of fibers continuously fed from sliver to the spinning area where they are incorporated into the yarn end.



**Roving:** In spun yarn production, an intermediate state between sliver and yarn.

**Sample unit:** Smallest element of a sample.

**Sap:** The liquid within a plant that carries food to all of its parts

**Saw gin:** Type of gin in which the ginning action is caused by a set of saws rotating between ginning ribs. The saw teeth pass between the ribs at the ginning point. The leading edge of the teeth is approximately parallel to the rib, and the teeth pull the fibers from the seed, which are too large to pass between the ribs.

**Scour:** To remove dirt, grease, or wax from (cloth or fibers) by means of a detergent.

**SCT:** Sticky cotton thermodetector, an instrument to test for stickiness. The general principle is the following: A cotton lint specimen is taken and opened (mechanical means are recommended) to form a web. The sample is then placed between two pieces of aluminum foil and a first pressure applied (at  $84 \pm 4$  °C). A cold (room temperature) pressure is applied immediately thereafter. To count the points, the upper piece of foil is removed carefully. Then the surface is cleaned without applying too much pressure, and finally the points are counted. These operations are repeated for the lower foil piece. The numbers of sticky points from the two pieces of aluminum foil for each specimen are summed.

**Sea island cotton:** Long-staple cotton (*G. barbadense*) grown in the southeastern United States.

**Seed coat fragment:** A portion of a cotton seed, usually black or dark brown in color, broken from a mature or immature seed, and to which fibers and linters may or may not be attached.

**Seed cotton:** Cotton lint from the boll that contains cotton seed.

**Short staple:** *Gossypium hirsutum*, which has shorter fibers compared to long-staple cottons.

**Sliver:** A continuous stand of loosely assembled fibers without twist. The card, the comber, or the drawing frame delivers sliver.

**Sorbitol:** A white, sweetish, crystalline alcohol,  $C_6H_8(OH)_6$ , found in various berries and fruits or prepared synthetically

**Spindle picker:** A harvesting machine that removes cotton from the burs with rotating spindles, leaving unopened bolls on the plant.

**Spinning:** The process or processes used in the production of single yarns.

**Staple:** Cotton fiber length.

**Stickiness:** The quality of adhering to surfaces; the property of sticky cotton that causes adhesion of lint to the surfaces of harvesting, ginning, or fiber-processing equipment.

**Sticky cotton:** Cotton contaminated with substance(s) that adhere to textile processing machinery, reducing efficiency and function.

**Sticky cotton thermodetector:** *see* SCT.

**Sticky cotton threshold:** The number of identifiable sticky spots per unit of cotton lint that indicates the need for concern in mill processing.

**Sticky spots:** Honeydew adhering to aluminum sheets following heating under pressure, in thermographic detection methods.

**Stoichiometric:** Calculation of the quantities of reactants and products in a chemical reaction. The quantitative relationship between reactants and products in a chemical reaction.

**Stripper cotton:** Cotton picked with a nonselective harvester that strips mature and immature bolls.

**Stripper harvester:** A harvesting machine that pulls or strips all cotton bolls, open and unopened, from the plant.

**Stylet:** Part of piercing insect type mouthpart.

**Sucrose:** A nonreducing disaccharide consisting of a glucose unit linked to a fructose unit by a glycosidic bond.

**Sugar:** Water-soluble carbohydrate, such as sucrose.

**Sweetpotato whitefly:** *Bemisia tabaci* (Gennadius) a widespread pest causing damage to many crops, including cotton.

**Textile processing:** Any mechanical operation used to transform a textile fiber or yarn to a fabric or other textile material. This includes such operations as opening, carding, spinning, plying, weaving, and knitting.

**Thermodetector:** *see* SCT.

**Translocate:** To transfer a substance to a new position. Movement of materials in phloem or xylem tissues of plants is referred to as “translocation.”

**Treatment threshold:** Entomology term meaning when control action is indicated.

**Trehalulose:** A nonreducing disaccharide isomer of sucrose, 1-O- $\alpha$ -D-glucopyranosyl-D-fructose, that constitutes a large percentage (up to 51 percent) of the carbohydrate produced by the sweetpotato whiteflies.

**Turanose:** A reducing disaccharide consisting of a glucose and a fructose. Turanose is a degradation product of the trisaccharide melezitose.

**Upland cotton:** *Gossypium hirsutum*, short-staple cotton.

**Vascular:** Having vessels circulating plant fluids.

**Whitefly:** Any of several small insects of the family Aleyrodidae (order Homoptera) characterized by white wings, nymphal immature forms, and underleaf habitat.

**Yarn:** Twisted threads of cotton lint used in weaving or knitting fabric.

## Appendix

### Some National and International Agencies Concerned With Cotton Lint Stickiness

A Meredith Jones & Co., Liverpool, UK

Agricultural Research Corporation, Wad Medani, Sudan

Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Montpellier, France

Cotton Incorporated, Cary, NC

Department of Entomology, The Volcani Center, Bet-Dagan, Israel

Department of Entomology, University of Arizona, Tucson, AZ

Department of Entomology, University of California, Davis and Riverside, CA

Graduate Institute of Textile Engineering, Feng Chen University, Taichung, Taiwan

Hellenic Cotton Board, Textile Technology Research Center, Thessalinika, Greece

Institut de Recherches du Coton et des Textiles Exotiques (ICRCT), Montpellier, France

International Cotton Advisory Committee, Washington, DC (World Cotton Conference)

International Textile Center, Texas Tech University, Lubbock, TX

International Textile Manufacturers Federation, Zurich, Switzerland (Stickiness Working Group/Honeydew Working Group)

Israel Cotton Production and Marketing Board, Tel Aviv, Israel

Lintronics Ltd, Tel Aviv, Israel  
<http://www.lintronics.com/>

Migal-Galilee Technological Center, Kiryat Shmona, Israel

National Cotton Council of America, Memphis, TN

Plant and Invertebrate Ecology Division, Rothamsted Research, Rothamsted, Hertfordshire, UK

Shenkar College of Textile Technology and Fashion, Ramat Gan, Israel

Texas Agricultural Experiment Station, Vernon, TX

USDA, Agricultural Research Service, Cotton Quality Research Laboratory, Clemson, SC, and Western Cotton Research Laboratory, Phoenix, AZ