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Review article

Cultural practices for managing *Bemisia tabaci* and associated viral diseases[☆]

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Abstract

Whiteflies (*Bemisia* spp.) and the viruses they vector cause extensive losses to many horticultural and agronomic crops throughout the tropics and subtropics. These losses have spurred a worldwide search for cost-effective management strategies. Cultural practices can play a significant role in integrated pest management (IPM) systems targeting whiteflies, because of their preventative nature. Yet, cultural practices have received disproportionately little attention from researchers, possibly due to the difficulty of testing by conventional methods. Practices such as crop-free periods, altering planting dates, crop rotation, and weed and crop residue disposal, perform well only if used on a regional scale and therefore are difficult to test or demonstrate experimentally. Growers may also be reluctant to adopt cultural practices such as living barriers, high planting densities, floating row covers, mulches, and trap crops, that require significant changes in conventional cropping practices. Nonetheless, we have seen adoption in recent years of some cultural practices to manage whiteflies, such as crop planning that includes host-free periods, and various forms of screened exclusion. This review focuses on research efforts, field utilization, and the potential of cultural practices to manage the whiteflies and associated viral diseases.

Keywords: *Bemisia tabaci*; *Bemisia argentifolii*; Viruses; Prevention; Integrated pest management (IPM)

Contents

[☆] Recent evidence suggests that *B. tabaci* represents a species complex with numerous biotypes and two described cryptic species. The binomial *B. tabaci* here is used in the broadest sense to include all member of the species complex unless a more specific designation is indicated.

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1. Introduction

Bemisia tabaci is a key pest in many tropical and subtropical cropping systems. Crop damage occurs directly through excessive sap removal, or indirectly by promoting the growth of sooty mold, inducing systemic disorders through feeding, or by vectoring plant viruses. The resulting economic impact has stimulated research efforts from basic to applied (Cock, 1986a; Ohnesorge and Gerling, 1986; Gerling, 1990; Gerling and Mayer, 1996).

Whitefly management includes the four cornerstones of integrated pest management (IPM): host plant resistance, biological control, chemical control, and cultural practices. Like host plant resistance, cultural controls are preventative in nature, but contrast with the first three tactics in being a heterogeneous group of practices, without well-defined boundaries or a coherent conceptual framework. They are intended to create a less favorable environment for pest reproduction and survival by deliberately manipulating some component of the agroecosystem (soil, external inputs, associated plants, and the crop per se) (NAS, 1968, 1969; Palti, 1981; Herzog and Funderburk, 1986). Thus, management by means of cultural practices consists of the manipulation of current or new components of the agroecosystem to reduce pest damage to non-economic levels (Hilje, 2000a).

There are relatively few references to cultural control of whiteflies in the literature, compared to other management tactics (Cock, 1986a; Ohnesorge and Gerling, 1986; Gerling, 1990; Gerling and Mayer, 1996). A number of cultural control practices originally developed for use on other virus-vector systems, have been adapted to deal with *B. tabaci* (Zitter and Simons, 1980; Thresh, 1982). Cock (1986b) compiled references to tobacco and cotton in Asian and African countries, before 1950, and stressed the importance of crop-free periods, crop residue disposal, planting dates, removal of alternate hosts, crop isolation, trap crops and living mulches. The topic was not included as a chapter in Gerling (1990). In Cohen and Berlinger (1986) and Berlinger and Lebiush-Mordechi (1996), discussion on cultural control focused on practices widely used at the time for vegetable production in Israel, such as screens and inert ground covers (sawdust, straw, rice husk, and yellow plastic mulches).

The objective of this paper is to review current research efforts on the utilization of cultural practices for managing *B. tabaci* and the viruses it vectors.

2. Classification and current status

One approach to classifying this diverse group of practices might be a scheme based on underlying biological and ecological mechanisms. Here we use *avoidance in time* or *space*, *behavioral manipulation of the insect*, *host suitability*, and *insect removal* (Table 1). This approach can be complemented with criteria related to the scale on which the practice is expected to operate: *regional*, *local* or *individual*. In such a scheme, crop sequencing and crop-free periods intended to remove or decrease inoculum sources over an entire area would be categorized as regional. Living barriers, trap crops and mulches intended to manage whiteflies in a single field would be classified as local. Fertilization regimes, although applied over an entire field, are intended to alter the suitability or susceptibility of individual plants and so would be characterized as individual.

2.1. *Avoidance in time*

This group of cultural practices is aimed at separating in time the crop from sources of the insect and/or the viruses it vectors.

2.1.1. *Crop-free periods*

The objective of a crop-free period is to synchronize cropping patterns over a large area to avoid the

Table 1
Classification of cultural practices to deal with *B. tabaci*, according to the biological and ecological mechanisms underlying them, as well as the scale on which practices are expected to operate

Mechanism	Scale	Examples
Avoidance in time	Regional	Crop-free periods, rotations and planting dates
Avoidance in space	Local	Screenhouses, floating row covers and high plant densities
Behavioral manipulation	Local	Intercropping and mulching
Host suitability	Individual	Fertilization, irrigation
Removal	Individual	Overhead irrigation

continuous presence of crops that are susceptible to whiteflies and/or whitefly transmitted viruses. Such a gap in production can reduce the overall population levels of the vector and reduce the amount of virus inoculum in the area. Because *B. tabaci* can reproduce on over 500 different plant species (Greathead, 1986), it may be impossible to completely remove all of the plant hosts of the vector from an area. However, crop-free periods can reduce mass migrations of insects directly from one crop to another.

The history of managing whitefly borne diseases with crop-free periods can be traced to the 1920s when cotton leaf curl disease was controlled in the Gezira region of Sudan by a two-month "dead season" during which cotton was not planted and ratoon growth removed (Bailey, 1930). During the same general timeframe, tobacco leaf curl was controlled in south central Africa through a legally mandated closed season during which tobacco was not grown and ratoon growth destroyed (Cock, 1986b).

Perhaps the most dramatic recent example occurred in the processing tomato industry in the Azua valley and other production areas of the Dominican Republic. *B. tabaci* first invaded this area in 1988 (Villar et al., 1998) and Tomato yellow leaf curl virus (TYLCV) was found in 1992 (Polston et al., 1994). The industry was devastated, with harvested hectares dropping from 8805 in 1989 to 3729 in 1993, and yield decreasing from 21.6 to 11.3 t/ha over the same interval (Fig. 1); some of the shortfall was made up by importation of tomato paste, which also peaked in 1993. To overcome this crisis, cultural management practices were supported by regulatory measures that banned cultivation of whitefly reproductive hosts 90 days before the main growing season (Alvarez and Abud-Antún, 1995; Villar et al., 1998). Approximately 600 ha of unauthorized crops and volunteer plants were eradicated every year during the implementation phase of these regulatory measures, and sorghum was promoted as a rotational crop during summer. By 1997, the area of tomato harvested had increased to 8940 ha and yields to 30.4 t/ha. Compliance with the ordinances, along with deployment of tolerant hybrids and judicious insecticide use, was credited with allowing the local industry to prevail (Villar et al., 1998).

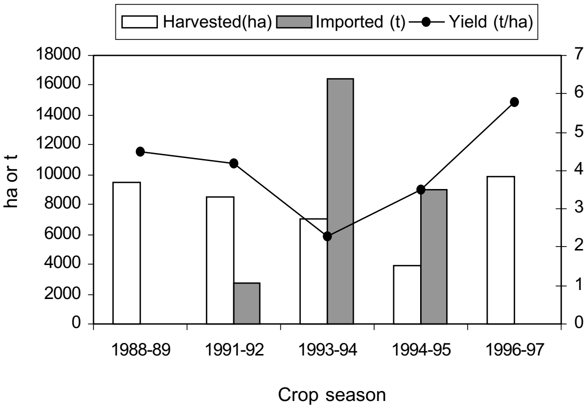

Fig. 1. Production of industrial tomato in the Dominican Republic, from 1988 through 1997, including data on harvested area (ha), yield (t/ha) and imported paste (t). Source: Villar et al. (1998).

In the isolated Arava region of Israel, the common practice prior to 1983 was to cultivate crops from August to March, leaving a four-month crop-free period (Ucko et al., 1998). The introduction of cucurbit crops in 1983 extended the growing season over the entire year. Subsequently, the region began to experience virus epidemics, principally TYLCV, Zucchini yellow mosaic virus (ZYMV), Cucumber mosaic virus (CMV) and Potato virus Y (PVY). A field survey of the area found several weed species with populations of whiteflies, some of which were known to be susceptible to the TYLCV virus. However, no TYLCV-infected weeds were detected in the field (Ucko et al., 1998). In addition, only a low percentage of potential hosts for the other viruses were found infected. Therefore, it seemed that cultivated crops themselves were the major source of inoculum for initiation of the viral epidemics.

Monitoring for whiteflies and virus showed that during June and July, whitefly populations were very low, and sources of viruses were rare (Ucko et al., 1998). Given these results, it was recommended that a vegetable crop-free period be created during the hot months of June and July. Implementation included ending the growing season in June and cleaning crop fields by removal of all vegetation, leaving fields clean for at least one month before planting again. The crop-free period was initially voluntary, but eventually became mandatory. No virus epidemics were reported during 12 years under this management system. The occurrence of TYLCV and other aphid borne viruses was much reduced (Ucko et al., 1998).

In southwestern United States during the 1980s, fall vegetable and melon plantings were being decimated by overwhelming numbers of whiteflies and whitefly transmitted viruses. When cotton crops were terminated, huge numbers of whiteflies were observed moving directly into newly planted vegetable and melon crops (Blua et al., 1994; Nuessly et al., 1994). Whitefly transmitted viruses, particularly the closteroviruses (criniviruses) lettuce infectious yellows (LIYV) acquired during the migrations, reduced vegetable stands resulting in severe economic losses and threatened to wipe out lettuce and melon production in these areas (Duffus and Flock, 1982). To break this cycle, short-season cotton production schedules were tested and selected to create a host-free period without reducing yield (Nuessly et al., 1994). A combination of early termination of cotton and delayed planting of vegetable and melon crops was recommended to reduce the overall impact of whitefly populations and virus incidence on fall plantings of vegetables (Blua et al., 1994; Nuessly et al., 1994). This approach complemented, and was perhaps largely driven by, management considerations for pink bollworm in cotton (Chu et al., 1996).

In southeastern United States, *B. tabaci* biotype B was first detected in 1986 on poinsettia, but soon became a major pest of vegetables in south and central parts of Florida. Tomato was the crop most impacted, first from irregular ripening induced by nymphal feeding (Schuster et al., 1996a), and second through transmission of tomato mottle geminivirus (ToMoV) (Kring et al., 1991). Yield losses and control costs in Florida tomato were estimated at $141 millions for the 1990–1991 season (Schuster et al., 1996b). Epidemiological studies concluded that plants infected with ToMoV primarily occurred in a pattern of scattered clusters (Polston et al., 1996). This pattern is indicative of repeated infection by whiteflies immigrating into the field from outside sources (primary spread), rather than spreading from plant to plant within the field (secondary spread) (Polston et al., 1996). Areawide sampling showed that large whitefly populations were building up in crops, and subsequently migrating from crop to crop (Stansly, 1996). Weeds appeared to serve as intermediate hosts, supporting low populations of whiteflies over fallow periods.

These observations supported recommendations for creating a crop-free period during summer by removal of all crop residues (Stansly and Schuster, 1990; Stansly et al., 1991). Separation of fall and spring crops in time and space was also recommended to reduce carryover of whitefly populations and ToMoV to consecutive plantings. In the southwest growing region of Florida, summer cleanup was quickly adopted, and fall whitefly populations have remained low after this initial outbreak. A campaign to separate the fall and spring crops by not planting for two months in the winter met more limited success due to market pressures. Whitefly populations never again reached the level of spring 1991 and were reduced even further with widespread use of imidacloprid beginning in spring 1995 (Stansly, 1996).

2.1.2. Crop residue disposal

Creation of a crop-free period requires removal of crop residues. The proportion of viruliferous whiteflies coming off virus-infected crop residues is liable to be high, because of the relatively large proportion of infected plants at the end of the crop season. For instance, rapid progression of Tomato yellow mottle (ToYMoV) disease in new fields located near old and totally infected fields (as close as 300 m away) in Costa Rica (Fig. 2) is likely a result of very high numbers of incoming viruliferous whiteflies (Hilje, personal observation).

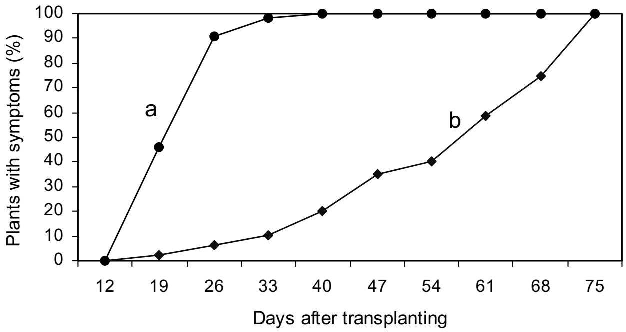

Fig. 2. Contrast between epidemic patterns of the Tomato yellow mottle virus (ToYMoV) in new plots established close (about 300 m away) (a) or far (more than 1 km away) (b) from old tomato fields, respectively, in Costa Rica. Unpublished data from different experiments.

2.1.3. Planting dates

Even if an areawide crop-free period is not adopted, some amount of vector and virus inoculum can often be avoided by planting early or late. Recent examples include eggplant in India (Borah, 1994), okra in Mexico (Díaz-Franco and Obregón, 1997), tomato in Egypt (El-Gendi et al., 1997), cotton in northern Mexico (Hernández and Pacheco, 1998; Hernández-Jasso and Pacheco-Covarrubias, 1998), bean in Egypt (Metwally, 1999), tobacco in India (Patel and Patel, 1966), and cantaloupe in California (Chu et al., unpublished).

2.1.4. Weed removal

In general, removal of weeds from cropping areas can help reduce the availability of alternate hosts for the vector, and reduce potential sources of viral inoculum. The importance of weeds in both *B. tabaci* population dynamics and viral epidemics will vary with each cropping system and plant-virus combination. In some cases the importance of weeds is negligible compared to host crops per se. For example, Ucko et al. (1998) found that in the Arava region of Israel weeds did not appear to be an important source of TYLCV, since no infected weeds were detected in the field. In that case, it seemed that cultivated crops themselves were the major source for initiation of the viral epidemics.

In other cases, weeds may play an important role in maintaining sources of virus inoculum. Studies conducted in the Jordan Valley of Israel found two weed species that were identified as sources of TYLCV inoculum (Cohen et al., 1988). One, *Cynanchum acutum* (Asclepiadaceae), serves as an overwintering host of the virus, and provides a source of inoculum to whiteflies migrating in late summer. It was suggested that eradicating *C. acutum* in June–July before peak migration may control the spread of TYLCV in this area (Cohen et al., 1988).

Wild reservoirs have not yet been identified for some geminiviruses in the New World, despite intensive survey efforts. These include the ToYMoV (Rivas et al., 1995; Jovel et al., 1999), the already mentioned ToMoV (Polston et al., 1996), and the Bean golden mosaic virus (BGMV) (Pilar Ramírez, 1999, Universidad de Costa Rica, pers. comm.). Although no weeds have been identified as alternate hosts of these viruses, there may still be unidentified virus-infected weeds that serve as sources of initial inoculum for whiteflies that stop to feed on them at some point during migration.

We were unable to find any reports documenting successful control of either whiteflies or whitefly transmitted viruses through weed removal alone. These observations suggest that it may not be worthwhile to spend resources on weed removal for these native viruses. Nevertheless, there seems always to be concern about a possible role for weeds in initiating infestations and/or virus epidemics.

2.2. Avoidance in space

These practices are intended to reduce the opportunities for whiteflies to contact the crop, either by excluding them from the latter, or by providing unusually high numbers of plants so the insects will not damage all of the susceptible crop.

2.2.1. Exclusion

Field and greenhouse grown crops can be protected from whitefly or virus damage using a variety of physical exclusion methods. In some cases, the entire crop is grown inside an enclosed greenhouse or under an insect-proof structure. In Israel, almost all tomatoes are grown inside enclosed structures constructed of solid plastic and/or fine screening to escape the pressure of TYLCV (Cohen and Berlinger, 1986; Horowitz et al., 1994; Berlinger and Lebiush-Mordechi, 1996; Ausher, 1997).

Insect screening is available in a variety of mesh sizes to allow selection of materials that optimize insect exclusion requirements while allowing adequate airflow through the screening (Bethke and Paine, 1991; Bethke et al., 1994; Bell and Baker, 2000). Some greenhouse plastics and screening contain an ultraviolet-absorbing additive that blocks a greater portion of the ultraviolet light spectrum than standard products, yet maintaining high transmission of visible light. Structures constructed of these ultraviolet-blocking materials had lower whitefly populations and less incidence of virus, compared to similar materials that transmitted more ultraviolet light (Fig. 3) (Antignus et al., 1996, 1998; Costa and Robb, 1999). It is suggested that elimination of certain portions of the ultraviolet wavelengths of light interferes with the ability of insects to orient and/or find plant hosts (Kring and Schuster, 1992; Antignus et al., 1996; Antignus, 2000).

Young plants are generally more susceptible to damage by whiteflies and plant viruses. Seedlings or cuttings that will be transplanted to the field can be protected from whiteflies during early development by covered structures. Clean transplants can be the first line of defense against developing damaging populations of whiteflies in field and greenhouse grown crops.

Likewise, field sown or transplanted seedlings can be protected in the early stages of growth by temporarily covering with materials such as spun-bonded polyester

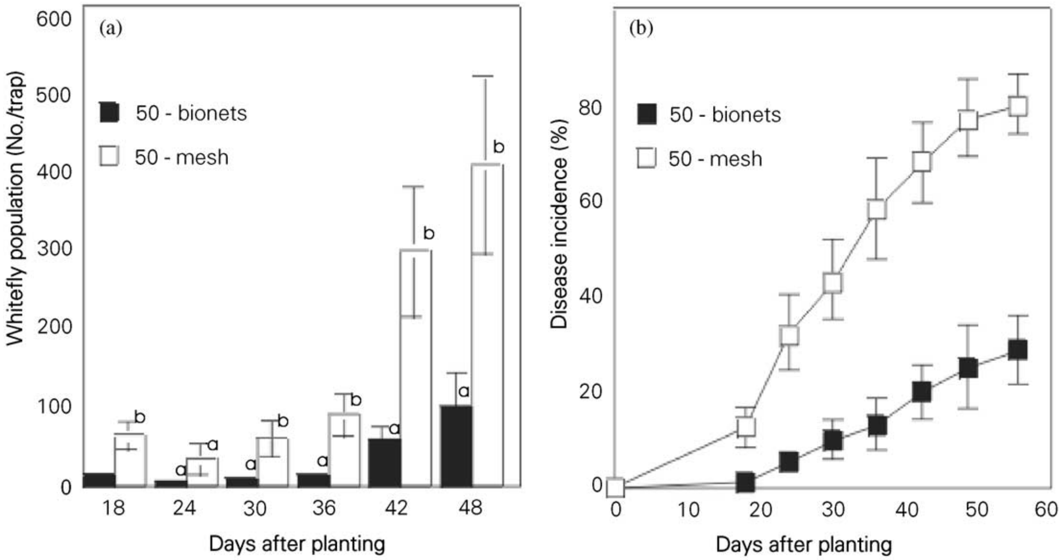

Fig. 3. Comparison of conventional and bionet screens of 50-mesh size, for their effectiveness in reducing incoming *B. tabaci* adults to walk-in tunnels (a) and Tomato yellow leaf curl virus (TYLCV) incidence (b), in Israel. Means and standard errors differ at $p<0.05$ when analyzed by Student *t*-test. (Redrawn from Antignus et al. (1998) with permission from the Entomological Society of America).

made into "floating" row covers, that lay over the tops of plants. Insects are excluded and light transmission is still adequate for plant growth. These lightweight materials are generally placed over the crop at time of planting and rest on top of the plants as they grow without a supporting structure. The material remains in place until it is necessary to remove it for cultural practices or bee pollination. Row covers have been successfully used in cucurbits, bell pepper, and tomato plantings to decrease whitefly population levels, reduce or delay the incidence of whitefly transmitted viruses, reduce development of squash silverleaf or tomato irregular ripening symptoms, and/or increase yields (Natwick and Durazo, 1985; Cohen and Berlinger, 1986; Perring et al., 1989; Webb and Linda, 1992; Costa et al., 1994; Orozco-Santos et al., 1994, 1995; Farías-Larios et al., 1995, 1996; Avilla et al., 1997).

Some of these techniques have been modified and adopted by small tomato growers in the tropics. Small tunnels covered with fine mesh are established in the field, where seedlings remain fully protected from whitefly transmitted viruses (Anzola and Lastra, 1978; Ioannou, 1997). This practice has been further improved by prolonging time seedlings remain under the mesh (25–30 days after sowing) (Cubillo et al., 1994, 1999a), thus providing protection through the first critical phase of tomato susceptibility to geminivirus infection (Schuster et al. 1996a).

2.2.2. Barriers

Earlier work suggested that the majority of *B. tabaci* adults normally fly <2 m from the ground (Gerling and Horowitz, 1984). Thus, in theory, the placement of a tall physical barrier around a crop field could impede or delay whitefly movement into the crop. Barriers can be constructed of various materials including screening, polyethylene plastic, or wood. In some cases, the barrier can consist of a relatively tall species that is planted around the perimeter of a primary crop. Examples of plants commonly used as living barriers include graminaceous species, like sorghum (*Sorghum bicolor*), Johnson grass (*Sorghum halepense*), corn (*Zea mays*) and elephant grass (*Pennisetum purpureum*).

Recently, Isaacs and Byrne (1998) found that *B. tabaci* may be trapped as high as 7.2 m above the ground adjacent to source fields, indicating that a proportion of the population are ascending out of the boundary layer near field edges. This may partially explain the inconsistent effect of barriers on whitefly population levels and virus incidence. In Israel, $11 \times 11\,\text{m}^2$ tomato plots were surrounded by 1.5 m tall black polyethylene partitions, or left open as controls. In these studies, more whiteflies were trapped and the incidence of TYLCV was higher in plots with barriers than those without (Cohen et al., 1988). In contrast, Gravena et al. (1984) in Brazil were able to reduce *B. tabaci* adult density and increase densities of its predators by planting sorghum barriers around tomato fields, and in Mexico viral infection was reduced in bell pepper when using corn barriers (O. Pozo, unpublished). However, in Florida corn barriers did not reduce migration of incoming whitefly adults into common bean plots (Smith and McSorley, 2000). Nevertheless, corn barriers are being widely used in Cuba around small and medium-size commercial bean fields (M. González, unpublished).

The use of living plant barriers for vector management has been most successful with non-persistent aphid transmitted viruses. With most non-persistent viruses, the aphids begin to lose infectivity immediately after acquisition and will become non-infectious in a matter of minutes while feeding (Nault, 1997). Thus, if an aphid feeds on the non-susceptible barrier plants for a brief time before moving into the susceptible crop, it will lose the virus. In contrast, whitefly transmitted viruses are persistent or semi-persistent in nature (Nault, 1997), so infectious whiteflies will remain infectious for hours to days, or for life, depending on the type of virus, regardless of how many hosts they feed on before finding a susceptible plant species. With whiteflies, barrier plants probably function by reducing the overall numbers of insects migrating into the crop, rather than reducing the percentage of vectors that are infectious. Thus, it is expected that barrier plants would not be as effective in managing most whitefly transmitted viruses as they are with non-persistent aphid viruses.

2.2.3. High planting density

The concept of increasing the density of crop plants per unit area to decrease disease incidence is based on the principle that given a fixed number of vectors, the more crop plants there are per unit area, the smaller the proportion of plants those insects can infect (Broadbent, 1969). Thus, a greater number of plants escape infection and potentially produce a higher total yield per unit area.

Preliminary studies with whitefly transmitted viruses have shown this approach to be effective for bell pepper and tomato in experimental trials in Mexico and Honduras (O. Pozo, unpublished; K. Sponagel, unpublished). In trials comparing virus incidence in different planting densities of cassava, the incidence of African cassava mosaic virus (ACMV), expressed as a percentage of the total stand, was greatest at the lowest plant density (Fargette and Fauquet, 1988; Fargette et al., 1990); intercropping practices to increase plant density also lowered ACMV incidence (Ahohuendo and Sarkar, 1995).

Because the development of silverleaf symptoms in squash in response to feeding of whitefly nymphs is generally density-dependent (Yokomi et al., 1990; Schuster et al., 1991; Costa et al., 1993, 1994), one would expect that more plants per unit area would result in fewer whiteflies per plant and lower symptom severity. However, in studies measuring silverleaf symptom severity in zucchini squash with row spacing ranging from 30 to 76 cm or 1–3 plants per hill, no significant difference in symptom rating of plants was observed (Powell et al., 1993). In another study, the use of living mulches that increase total plant density per unit area reduced symptoms of squash silverleaf in zucchini, but did not increase yield (Hooks et al., 1998).

2.3. Behavioral manipulation

These practices are aimed at disrupting whitefly host-searching behavior by interfering with visual or olfactory cues.

2.3.1. Intercropping

Intercropping refers to spatial arrays of crops including two or more plant species in close proximity to each, within a given plot. The objectives of crop associations can be to create a refuge for natural enemies and/or manipulate the host-seeking behavior of the pest to protect the principal or most susceptible crop.

Differential crop preference can be utilized to create a trap crop by planting a more preferred crop in close proximity to a less preferred whitefly sensitive crop. Insects will preferentially infest the preferred trap crop, reducing pest pressure on the primary crop. The preferred trap crop can be treated with an insecticide either to kill whiteflies as they feed on it, or to avoid their subsequent movement.

For example, cucumber in general is more attractive to whiteflies than tomato, but is not a host of TYLCV. Al-Musa (1982) in Jordan used cucumber (*Cucumis sativus*, Cucurbitaceae) as a trap crop between rows of tomato to substantially decrease the incidence of TYLCV in the tomato. The cucumber plants were treated with an insecticide before senescence to avoid massive movement of whitefly adults into tomato. This approach is currently widely used in Sudan and other Middle East countries (Ioannou, 1997). However, the idea of using a preferred host as a trap crop can backfire. For example, in Florida, tomatoes planted next to a more preferred eggplant actually had higher numbers of whiteflies than tomatoes planted next to tomato. In this case, the trap crop acted as a source of whiteflies rather than as a sink. However, when the eggplant was treated with imidacloprid, the adjacent tomatoes had fewer whiteflies than tomato next to tomato (Stansly et al., 1998). This practice was not recommended because the insecticide was deemed more efficiently used directly on the crop rather than on the trap crop.

Other associations tested include maize, cowpea or peanut with cassava (Ahohuendo and Sarkar, 1995; Fargette and Fauquet, 1988); green beans, squash, wild plants, or eggplant with tomato (Arias and Hilje, 1993; Peralta and Hilje, 1993; Pantoja et al., unpublished; Hilje and Stansly, unpublished); the weed *Physalis wrightii* or melon with cotton (Ellsworth et al., 1992; Castle, 2001); cauliflower with melon (Perring et al., unpublished); squash with snap beans (Smith et al., 2000); and eggplant with common beans (Smith and McSorley, 2000). In addition, there are many anecdotal references to either crops or wild plants used as trap crops (Ioannou, 1997). However, except for the work of Al-Musa (1982), there is little experimental evidence to document positive results with such practices.

Inconsistent results with the use of intercropping to manage whiteflies could be due to experimental artifacts, such as plot size, trap crop layout in regards to the main crop, etc. However, a more likely explanation is that the attractiveness of the trap crop wanes over the crop cycle due to maturity, senescence, or a high pest population. The trap crop changes from a whitefly sink to a source and may need to be sprayed to prevent whitefly migration to the main crop.

In summary, a good trap crop to manage whiteflies is one that is very attractive to whiteflies, retains populations for the life of the crop, is not a host of any whitefly transmitted viruses, and is a poor reproductive host for whiteflies. Unfortunately, such crops are not easy to find. Even if adequate intercrops were available, the logistics of managing two crops simultaneously can be difficult in many commercial settings. Although trap crops have shown favorable results in other crop-pest systems (Hokkanen, 1991), they have not proven to be a reliable approach to deal with whiteflies and whitefly transmitted viruses.

2.3.2. Mulches

The objective for using mulches to manage whiteflies is to reduce the insect's ability to find the crop. The mode of action of inert ground covers such as plastics, sawdust, straw and rice husk mulches, has been attributed to interference with visual host-finding or suicidal attraction to the sun-heated mulch (Cohen, 1982; Cohen and Berlinger, 1986). Colored plastic mulches in a variety of colors, including aluminum, silver, transparent, white and yellow have proven to be effective for reducing whitefly numbers and/or the incidence of whitefly transmitted viruses (Suwwan et al., 1988; Orozco-Santos et al., 1994, 1995; Csizinszky et al., 1995, 1997, 1999; Smith et al., 2000). For example, the incidence of tomato mottle virus in Florida (Csizinszky et al., 1995), and TYLCV in tomato in Jordan (Suwwan et al., 1988) was reduced using aluminum or silver reflective mulches. Colored or reflective mulches are most effective early in the crop cycle, before the developing plant canopy covers the mulch.

Inert mulches can also increase yields due to favorable physiological effects on plant growth (Suwwan et al., 1988; Csizinszky et al., 1995, 1997; Berlinger and Lebiush-Mordechi, 1996; Schuster et al., unpublished). They are commonly used in many countries in production of melons and other cucurbits, as well as tomato and bell pepper. Constraints to the use of plastic mulches include costs of materials and difficulties with disposal (labor and air pollution).

Low-growing living mulches or ground covers are a potentially low-cost alternative to plastic mulches without environmental liability. In the case of tomato production, living ground covers are intended to remain in the field only during the first five weeks after transplanting, which is a long enough interval as to protect tomato plants during their critical period of susceptibility to geminivirus infection (Schuster et al., 1996a). In practical terms, living mulches cause whiteflies to fly away from tomato plots without feeding on tomato plants (Cubillo et al., 1999b).

A theoretical framework for the function of living mulches has been proposed by Finch and Collier (2000), who suggested that insect herbivores locate host plants initially through indiscriminant visual attraction to (yellow) green. Only after landing do they discriminate between "appropriate and inappropriate" hosts. If the host is not appropriate, the insect flies a short distance and lands again. After a number of such inappropriate landings, the insect is likely to leave the general area entirely. The presence of numerous non-host plants in the form of living mulch greatly increases the likelihood of successive inappropriate landings that eventually lead to abandonment of the search and exit from the area.

Living covers have been shown to be effective in reducing the number of incoming whitefly adults, delaying virus dissemination, decreasing viral disease severity, and providing high yields and net profits. Several plants species, including perennial peanuts (*Arachis pintoi*, Fabaceae), "cinquillo" (*Drymaria cordata*, Caryophyllaceae) and coriander (*Coriandrum sativum*, Apiaceae), have been evaluated for tomato production in Costa Rica (Amador and Hilje, 1993; Blanco and Hilje, 1995; Cubillo et al., 1999b; Hilje, 2000b). These plant species were not hosts of ToYMoV and were not observed to harbor other plant pathogens. They were particularly suited for small farms, because seed was locally available, they could return extra organic matter and nutrients to the soil, and provide additional income through sale of seed, forage or other products. When perennial peanuts were used as a living ground cover with tomato, the tomato crop provided yields and net profits as high as 40 t/ha and US$ 38,000/ha (Fig. 4). "Cinquillo" (36 t/ha, US$ 32,000/ha) and coriander (30 t/ha, US$ 31,000/ha) followed close behind and were within the range of expected yields in Costa Rica, that vary from 21 to 35 t/ha. Also, coriander could be sold after removal for an additional US$ 5000/ha.

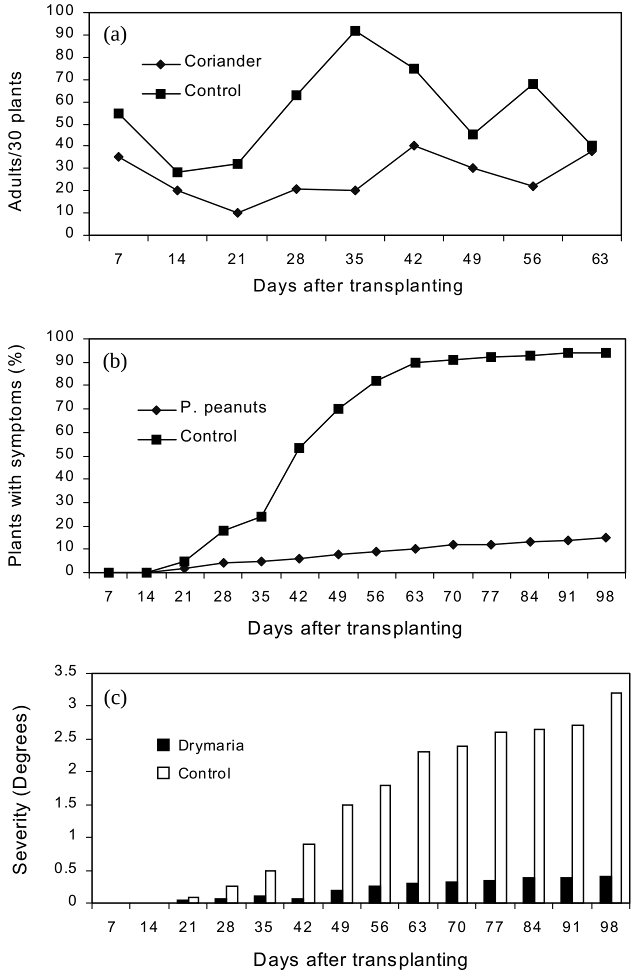

Fig. 4. Contrast between tomato plots with bare soil versus plots with different types of ground covers (coriander, perennial peanuts and *Drymaria*), in terms of whitefly abundance (a) and average ToYMoV incidence (b) and severity (c). Unpublished data from different experiments in Costa Rica.

In Hawaii, Hooks et al. (1998) found a reduction of whitefly adults and symptoms of squash silverleaf, when they used buckwheat (*Fagopyrum esculentum*, Polygonaceae) and yellow mustard (*Sinapis alba*, Brassicaceae) as living mulches with zucchini.

2.4. Host suitability

These practices are intended to induce changes in host quality in ways that adversely affect biological processes related to whitefly reproduction and survival.

2.4.1. Fertilization

Plant nutrition, particularly available nitrogen, would be expected to exert profound effects on plant growth and thus affect *B. tabaci* survivorship and reproduction. Whitefly weights are known to decrease as the relative concentrations of essential amino acids decrease in the plant (Blackmer and Byrne, 1999). Nevertheless, the experimental evidence for a direct effect of nitrogen fertilization on whitefly fitness is equivocal.

Bentz et al. (1995) found more *B. tabaci* (biotype B) on fertilized poinsettia plants than on unfertilized plants in greenhouse choice tests. Likewise, the number of eggs laid by *Trialeurodes vaporariorum* on chrysanthemums and the number of adults emerging were greater on plants treated with high concentrations of fertilizer, and were correlated with nitrogen content of leaves (Bentz and Larew, 1992). In contrast, there was no significant effect of fertilization on oviposition of *B. tabaci* in no-choice tests, although survivorship to the adult stage was significantly higher on fertilized plants (Bentz et al., 1995). Blua and Toscano (1994) found no differences in stage-specific survival or the time *B. tabaci* spent in each stadium on cotton plants irrigated with 0.5, 2.5, or 5.0 mmol/l of nitrogen fertilizers. However, time to adult emergence by whiteflies increased with decreasing nitrogen fertilization. Bi et al. (2001) found that peak populations of whitefly adults and nymphs, as well as honeydew production, increased in response to increasing nitrogen levels in large plots of cotton. Therefore, there may be some potential to manipulate whitefly populations through fertilization practices.

2.4.2. *Irrigation*

The effects of irrigation practices on plant physiology can indirectly impact whitefly populations. When comparing drip and furrow irrigated cotton, greater number of whiteflies were observed in the furrow-irrigated fields, even though the frequency and amount of water applied in each treatment was not compared (Leggett, 1993). Likewise, Mor (1987) reported that in Israel water-stressed cotton had higher numbers of whitefly nymphs, and that higher leaf water potential was correlated with higher numbers of nymphs. This work suggested that avoiding water-stressed cotton could help reduce whitefly infestations. This idea was also supported by work done by Flint et al. (1994, 1995, 1996) in Arizona, who found that both the type (drip or furrow) and frequency of irrigation could affect whitefly populations, and that increasing the irrigation frequency of cotton plants reduced water stress and decreased numbers of whiteflies.

2.5. *Removal*

These practices are aimed at modifying current agronomic practices to provoke a direct reduction on either *B. tabaci* populations or virus inoculum. They include overhead irrigation and roguing of diseased plants, but this account concentrates on the former, as there are no reported data on roguing as a method to decrease viral diseases transmitted by *B. tabaci*.

2.5.1. *Overhead irrigation*

Observations of declines in whitefly populations after rainfall have been reported in different regions (Zalom et al., 1985; Henneberry et al., 1995; Hilje, 1995). This could be due to dislodgement of adults from plants, possible negative effects of increased relative humidity on the immature stages (Gerling et al., 1986), or increased incidence of entomopathogenic fungi.

Castle et al. (1996) and Castle (2001) found significant reductions in whitefly eggs and nymphs in sprinkler irrigated cotton and cantaloupe crops compared with furrow irrigation, and suggested that this may be due to a disruptive effect of the water on adult whiteflies. In addition, for treatments receiving the same total amount of irrigation, the plots sprinkler irrigated daily for a shorter duration had less whiteflies than plots sprinkler irrigated twice weekly for a longer period (Castle et al., 1996). A potential limitation to the use of sprinklers is the higher costs associated with sprinkler irrigation compared to furrow irrigation, however, these costs may be offset by reductions in insecticide use or reduced honeydew contamination in cotton. The effects of overhead irrigation are corroborated by observations that rain and blowing dust can contribute substantial mortality by dislodging eggs and nymphs of *B. tabaci* from cotton leaves (Naranjo, 2001; Naranjo and Ellsworth, unpublished).

3. Concluding remarks

In summary, this review demonstrates that a large number of cultural practices for managing *B. tabaci* are being used or tested worldwide, many successfully. Constraints to wider adoption include: (a) substantial changes in the conventional cropping practices necessary for effective implementation of tactics such as living barriers, high planting densities, floating covers, mulches, and trap crops; (b) regional scale required for optimal implementation of crop-free periods, planting dates, crop rotation, and weed and crop residue disposal; (c) difficulty in experimentally quantifying and demonstrating effectiveness, due to interference between treatments caused by whitefly mobility; and (d) inability of most cultural practices to provide adequate control unless combined with other management tactics.

Nevertheless, practices such as crop-free periods coupled with planting dates, as well as exclusion with insect-proof structures or floating row covers, have been widely adopted. Most other cultural practices mentioned in this review are currently being tested experimentally, or in on-farm demonstrations in several countries. A survey of grower practices would probably reveal wider adoption of cultural control than is commonly believed. Better documentation of the efficacy and economic benefits would probably increase adoption of cultural practices. These are among the oldest means of controlling insects and will probably outlast many modern pest control methods.

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