Chapter 12
Optical Manipulations: An Advance Approach for Reducing Sucking Insect Pests

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1 Introduction

Insect pests are a major cause for reduction in the quantity and quality of crop plant products. Sucking insect pests that transmit viral diseases are an important cause of economic losses for growers of agricultural crops worldwide. Growers usually apply toxic insecticides to protect their crop plants from these pests. Frequent applications of insecticides create health hazards for workers, consumers, and the environment. Moreover, frequent applications of insecticides often induce resistance in the treated pest populations. Therefore, alternative methods for protecting crop plants from pests are constantly being sought. The use of mulches, traps and cladding materials that possess specific optical properties often reduced the infestation rates of pests and lowered the incidence of vector-borne viral diseases in crop plants. Recently, two comprehensive reviews were published on the effect of indirect and direct light on greenhouse pests by Vanninen et al. (2010) and Johansen et al. (2011), respectively. These reviews focus mainly on the potential for optical manipulation in high-technology year-round greenhouse production in northern Europe and Canada in which natural light is augmented with artificial light. In those greenhouses, pests may be manipulated by changing the light quality, quantity and photoperiod.

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In this chapter, we focus mainly on the manipulation of pests in open field and protected crops using the reflection of natural solar radiation. This approach is suitable for geographical regions that have a high intensity of direct sunlight during the seasons when sucking pests are active. In the Mediterranean region, sucking pests are mainly active from March to October and during this period most days are sunny and clear.

We propose that the optical cues of reflected light will be used to interfere with distant host finding by the pests. This is because it is expected that when pests are near or on the plants, other sensory cues, such as humidity gradient and plant odors, can substitute the optical cues. The optical modifications have to be compatible with optimal conditions for crop production. These conditions often include the undisturbed performance of beneficial insects such as biocontrol agents and pollinators.

Some of the experimental results and their interpretations presented in this chapter are based on our studies with the green peach aphid (*Myzus persicae* (Sulzer)), the cotton aphid (*Aphis gossypii* Glover), the sweet potato whitefly (*Bemisia tabaci* (Gennadius)), the onion thrips (*Thrips tabaci* Lindeman), the western flower thrips (WFT; *Frankliniella occidentalis* (Pergande)) and the chilli thrips (*Scirtothrips dorsalis* Hood). The crops were bell pepper (*Capsicum annuum* L.), tomato (*Lycopersicon esculentum* Miller), chives (*Allium schoenopransum* L.) and Lisianthus (*Eustoma russellianum* Salisb.).

2 Sucking Insect Pests

Sucking pests such as aphids and whiteflies feed by sucking fluids directly from the phloem vessels of plants. Thrips feed by breaking the epidermal cells of plants and sucking their contents. These pests cause injuries to plant tissue by the penetration of their mouthparts which can cause scars and often serve as ports of entry for bacterial and fungal pathogens. These pests also contaminate the surface of their host plants with their sticky sweet excrements (honeydew) that serve as a growing substrate for fungi. The majority of plant viruses are transmitted by sucking insect vectors such as aphids, whiteflies, and thrips (Hogenhout et al. 2008). Viruses transmitted by insect pests have various modes of transmission. Non-persistent viruses must be transmitted within minutes or a few hours after acquisition (Ng and Falk 2006). Insect-borne viral diseases often cause substantial economic damage to growers of crop plants (Raccah and Fereres 2009). The sweet potato whitefly, the onion thrips and the western flower thrips are important pests of many protected crops (Cohen and Berlinger 1986; Lewis 1997) and may be considered as quarantine pests.

At temperatures between 20°C and 25°C, these insects complete their life cycle in 1–4 weeks and can build up high populations on plants. Adult pests disperse to adjacent plants by walking or by short flights. Some of the adults migrate on long flight, aided by the wind, for colonizing new areas (e.g. Byrne 1999). In some species, extreme changes in weather conditions or massive drying of host plants induce swarming behavior (e.g. Matteson et al. 1992). Short flights usually occur just above the canopy of the host plants (e.g. Byrne 1999). In open and bare fields, most pests (about 80%) are trapped within 1.0 m above the soil level (e.g. BenYakir and Chen 2008). During long flight, these small pests are often are aided by the wind, at heights of 2–30 m above ground (e.g. Trevor 1997; Reynolds and Reynolds 2009 and references therein). While moving with the wind, they can be carried over greenhouses and enter them through the roof vents (Ben-Yakir et al. 2008b). Dispersal and migration flights are usually limited to a few hours every day (Ben-Yakir and Chen 2008; Ben-Yakir et al. 2008b). Take off and flight of small sucking pests, occur only when the wind velocity is low. The long flying female migrants are probably the main colonizers of new crops.

3 Natural Sunlight in the Agricultural Environment

The electromagnetic radiation emitted by the sun is filtered through the Earth's atmosphere before reaching the Earth's surface. If the sun's radiation is not obstructed, it reaches the surface as direct light (sunlight) but if it is refracted by clouds, dust etc., it reaches the surface as diffused light (skylight). Bright sunlight provides illuminance of approximately 100,000 lx (lumens per square meter), about 1,000 W/m^2 or photosynthetic photon flux density of near 2,000 µmol $photons/m^2$ s, at the Earth's surface (http://en.wikipedia.org/wiki/Sunlight). In Israel, maximum daily solar illuminance range between 70,000 and 100,000 lx from March to October (Manes et al. 1970). During this period about 80% of the solar illuminance is direct light and the rest is diffused. Sunlight reaching the land part of the Earth's surface is mostly absorbed by the soil and plants and only a small fraction of it is reflected. Light reflection is either mirror-like or diffused depending on the nature of the reflecting substrate (Björn 2008). Diffused light makes difficult to delineate the image of an object from its background. When sunlight is reflected off materials that are denser than the air (water surface, glass, metal), it undergoes a change in its polarity. Thus, the reflecting object determines the color (hue and saturation), intensity and polarity of the reflected light. Bare soil or soil covered with vegetation, reflects 20% or 15% of the sunlight, respectively. Light colored soils (sand, loess) reflect more sunlight than heavy dark soils. A smooth white surface can reflects up to 70% of the sunlight. The intensity of reflection is also affected by the daily and seasonal changes in the position of the sun relative to the reflecting object.

The sunlight reaching crop plants may be augmented by reflective soil covers or reduced by cladding materials. In the Mediterranean region, crops plants often need to be protected from excessive sunlight that causes sunburn and heat stress. Heat stress is especially severe in greenhouses and it is often alleviated by using shading nets.

4 Insect Vision

An updated review of insect vision by Johansen et al. (2011) was published recently. Aphids and whiteflies have light receptors in the ultraviolet (UV) region with peak sensitivity at 330–340 nm and in the green-yellow region with peak sensitivity at

520–530 nm (Doring and Chittka 2007; Coombe 1981, 1982; Mellor et al. 1997). Using the electroretinogram technique, Kirchner et al. (2005) noted that alate female summer-migrants of the aphid *M. persicae* have additional photoreceptor in the blue-green region (490 nm). Aphid color vision is achieved by possessing two to three classes of spectral receptors that either elicit direct response or are used in an opponent mechanism to 'compare' inputs from different spectral domains (Doring and Chittka 2007 and references therein). Thrips have light receptors in the yellow region (540–570 nm), the blue region (440–450 nm) and the UV region (350–360 nm) (Vernon and Gillespie 1990). Aphids and whiteflies do not possess receptors for red light (610–700 nm) and therefore their response to red is either neutral (Mellor et al. 1997) or inhibitory (Vaishampayan et al. 1975). However, alate green spruce aphids, *Elatobium abietinum* (Walker), were caught on red sticky traps more than on yellow or white traps (Straw et al. 2011), and females of the common blossom thrips, *Frankliniella schultzei*, are attracted to red flowers and to red traps (Yaku et al. 2007).

The response of insects to light is strongly affected by the intensity of radiation, the shape and contrast of the radiation source and the physiological state of the insect. Sucking pests usually require minimal light intensity for initiating a behavioral response. Lewis (1997) reported that thrips of the temperate climate require minimal light intensity of 1,000 lx for initiating flight. In contrast, high light intensity often inhibits the expected behavioral response to an attractive color. Aphids' preference for yellow over green may be explained by the higher reflectance of yellow in the green spectral domain (Prokopy et al. 1983). Indeed, when winged *Aphis fabae* were exposed to monochromatic lights of the same intensity, they preferred green (the peak receptor sensitivity) over yellow (Hardie 1989). Yellow usually has high reflectance in the long wavelengths (green to red spectrum) and low reflectance in the short wavelengths (UV to blue spectrum). Based on that, Doring and Chittka (2007) proposed that aphids employ an opponent mechanism to differentiate between yellow and other reflective colors like white or pink. In this mechanism, a positive input from the green receptor is coupled with a negative input from the UV or blue receptor resulting in the specific attraction to yellow.

Several studies have shown that in choice experiments, insects prefer to move to environments with a higher intensity of UV light (reviewed by Diaz and Fereres 2007). On the other hand, aphids and whiteflies seemed to be repelled by high intensity UV light (Summers et al. 2004). The attraction of thrips to yellow and blue traps was reduced by increasing the UV reflection (Vernon and Gillespie 1990). The attraction of WFT to colors was negatively affected when their UV reflectance was above 35% (Matteson et al. 1992). The attraction of the psyllid *Ctenarytaina thysanura* Ferris and Klyver to yellow cards was greatly reduced by diluting the yellow with white and lowering its hue (Mensah and Madden 1992). The reported attraction of sucking pests to white traps is very variable and it is probably affected by their reflection intensity and contrast. It appears that sucking pests are attracted to white traps over a dark background when the intensity of the solar radiation is low. In contrast, these pests are repelled by white color when the intensity of the reflected sunlight is high.

Circular and cylindrical traps were significantly more attractive for thrips than other shapes with the same color and size (Vernon and Gillespie 1995; Mainali and Lim 2010). Trapping efficiency was significantly higher for small sized traps (100 cm^2) that have high perimeter length to area ratio (Carrizo 2008). High contrast between the colored trap and its background (e.g. yellow over black) further enhanced the attraction of thrips. In a strawberry greenhouse, small circular yellow sticky traps (d = 5 cm) on a black background (12 cm × 12 cm) attracted 2.3–21.0 times more WFT than the commercial rectangular yellow sticky traps (5 cm wide × 8 cm length) (Mainali and Lim 2010). Similarly, yellow circles on a black background attracted about twofolds more *B. tabaci* per unit area than ordinary rectangular yellow sticky cards (Kim and Lim 2011). In pair wise choice tests, the WFT preferred yellow artificial flower shape to yellow geometrical patterns that had a similar size (Mainali and Lim 2011). Moreover, these thrips stayed on the artificial flower about four times longer than on the geometrical patterns. High contrast between the trap and its background enhance the attraction of aphids as well. In a Brussels sprouts field, more alate aphids were caught in yellow water-traps placed over bare soil than over weeds (Smith 1976). Aphids also landed more often on plants at low density because their contrast with the background soil was higher (A'Brook 1968; Bottenberg and Irwin 1992). On the other hand, a large area covered by a uniform material with an attractive color usually does not induce landing in pests (Ben-Yakir et al. 2012).

5 Light as a Modifier of Insect Behavior

Light is an important cue for insect orientation and for finding host plants. Radiation at the UV range stimulates flight activity in sucking pests (review by Kring 1972). During flight, these pests respond strongly to visual stimuli for orientation, navigation and host finding (Antignus and Ben-Yakir 2004). When aphids terminate their flight they lose their attraction to UV light and respond to yellow-green light for landing on potential host plants (Klingauf 1987). During the landing phase aphids are strongly attracted to intense (highly saturated) yellow light (Kennedy et al. 1961; Robert 1987; Fereres et al. 1999). Aphids locate host plants using the contrast between the soil background and the color reflected from the plant foliage (Kennedy et al. 1961; Doring et al. 2004). Whiteflies use similar optical cues during flight and host finding (Coombe 1982). Yellow and green reflected light are very attractive stimulus for orientation of *B. tabaci* during flight (Isaacs et al. 1999).

When aphids land on a yellow surface they are often induced to probe it, in an attempt to feed (Moericke 1950, as cited by Doring et al. 2004). As a result, most invading aphids that land on yellow objects are "arrested" on them (Bukovinszky et al. 2005). If the yellow object is not a plant, aphids usually fly away after a period of probing in vain (Kring 1972). Thrips are attracted to land on yellow, blue and white objects (Chu et al. 2006). WFT attraction to blue traps was enhanced by adding UV emitting diodes (LEDs) (Chu et al. 2005).

The attraction to color could be enhanced by plant odor over a short distance. For example, the carrot aphid, *Cavariella aegopodii* (Scopoli), was caught more often in water traps baited with carvone, a component of host odor, than in unbaited traps (Chapman et al. 1981). In greenhouse studies, yellow water traps with anisaldehyde caught 11–15 times more female WFT than yellow traps without anisaldehyde (Teulon et al. 1999).

The physiological state of the insects often affects their visual response. During dispersal, migration and swarming behavior insects are usually attracted to light in the UV range. Once aphids terminate their aerial transport they lose their attraction to UV light and respond to visual cues coming from potential host plants (Klingauf 1987). Among females of the carrot psyllid, *Trioza apicalis* Forster, gravids were more successful than virgins in visually selecting the carrot host plant (Nissinen et al. 2008). In wind tunnel experiments with WFT, older thrips (10–13 days post-adult emergence) landed twice as often on a yellow sticky trap compare with younger thrips (2–3 days post-adult emergence) (Davidson et al. 2006). In the same study, thrips that were starved for 4 h landed ten times more often on a yellow sticky trap compared with satiated thrips. On the other hand, no differences in color preferences were found between WFT males and females and between swarming and non-swarming thrips (Matteson et al. 1992).

6 Optical Manipulation of Pests

The optical manipulation proposed in this chapter is by using reflected sunlight to interfere with host finding by sucking pests. This can be achieved by repelling, attracting and camouflaging optical cues. Repelling cues include unattractive colors and high intensity reflection (glare). Attracting cues include attractive colors and shapes that divert the pests away from the hosts. Camouflaging cues reduce the contrast between the plants and their environment or block the visual cues from the plants before they reach the insect eye. Cues for optical manipulation are reflected from materials that are placed below or above the plants. Some of these cues can be reflected from the plant itself.

Experimental evidences for optical manipulations are difficult to compare and to interpret. This is because very diverse reflective materials were used and the actual sunlight reflections during these experiments were seldom reported.

6.1 Below the Plant

Covering the soil with colored polyethylene, straw or living plants have been used successfully to protect crops from sucking pests and the viral diseases they transmit (e.g. Hiljea and Stansly 2008). Highly reflective colored polyethylene mulches such as aluminum, silver, white and yellow have been used successfully to lower the

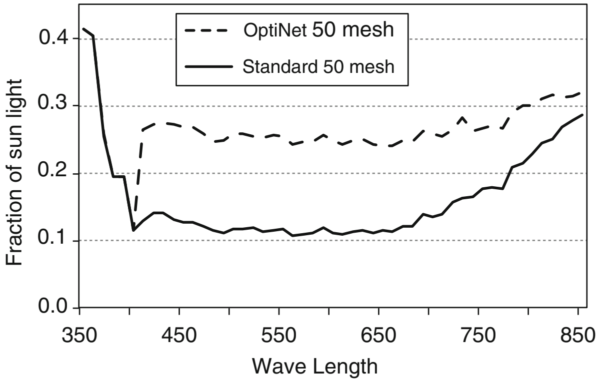

Fig. 12.1 Spectra of sunlight reflectance by the 50 mesh OptiNet® compared with a standard transparent 50 mesh net. The reflected spectra were divided by the sunlight spectrum that was measured at the same time (11:30 AM, August 5, 2005) in the Besor, Israel

infestation of sucking pests (e.g. Simmons et al. 2010). Metallic colored mulches are often referred to as "UV-reflecting" (e.g. Summers et al. 2004), however, they reflect a much wider range of the sunlight radiation. The actual color of the mulch appears to be less important than its brightness (Greer and Dole 2003). The overall effect of mulches on yield and fruit quality is dependent also on their effect on soil temperature, plant development and weed control (Csizinszky et al. 1995). When selecting a colored soil cover for reducing pests the other agronomic roles of this cover should be considered too.

As mentioned previously, sucking pests are repelled by high intensity UV and white light. The reflection level of sunlight from OptiNet® (50 mesh UV blocking net manufactured by Polysac Plastics Industries, Nir Yitzhak, Israel), at the range of 400–750 nm, is about 2.5 times greater than the reflection by standard 50 mesh net (Fig. 12.1). When we placed yellow sticky traps (10 × 10 cm) horizontally over OptiNet® used as a ground cover, they caught two- to threefolds fewer whiteflies (*B. tabaci*) compared with the same traps placed over a standard 50 mesh net (Fig. 12.2). When traps were placed over 50% OptiNet® (alternating 1 cm wide longitudinal bands with and without the UV blocking optical additives) the number of whiteflies caught was about half way between the number caught over OptiNet® and over standard net (Fig. 12.2). Thus, it appears that the intensity of light reflection by the screen, not only at the UV range, is negatively correlated with the likelihood that whitefly will land on an attractive target.

Covering the soil with yellow or green polyethylene sheets, straw or living plants probably camouflages the crop plants by reducing contrast. When using straw mulch or living plants as soil covers, it is likely that olfactory cues also play a role in modifying the insect behavior.

The visible area of the soil cover diminishes as the plants grow and their canopies cover the soil. Thus, the protective effect of reflective soil cover is limited to early growth stages or to widely spaced crop plants.

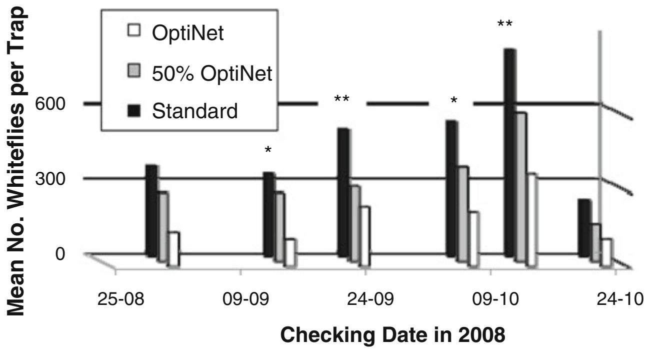

Fig. 12.2 The number of whiteflies caught on yellow sticky traps placed *horizontally* over various 50 mesh screens, Besor, 2008 (N = 3). *Bars* with * or ** *sign* over them are significantly different at the *P* <0.10 or *P* <0.05, respectively (ANOVA)

6.2 Above the Plant

Crop plants are often grown under protective cladding materials for improving production. In sub-tropical regions, protective plastic sheets and fine mesh nets are used mainly to physically exclude sucking pests (Berlinger et al. 2002). Covering crops with these cladding materials increases shading and reduces ventilation. The latter often results in heat stress for both crop plants and workers (Teitel 2007). Covering greenhouses with plastics or screens containing UV-blocking additives usually provides a greater protection against pests than standard cladding materials (reviewed by Antignus and Ben-Yakir 2004; Diaz and Fereres 2007; Johansen et al. 2011). The effects of other optical properties of the UV-blocking cladding materials, such as shading and reflection levels, have been ignored in most studies. Bionet® (Klayman Meteor, Petah Tikva, Israel) and OptiNet® are commercial nets containing UV-blocking additives. Bionet® provided a significant greater protection from whiteflies, *B. tabaci*, than standard net of the same density (Antignus et al. 1998). Kumar and Poehling (2006) reported that covering greenhouses with UV-blocking plastic and Bionet® significantly reduced both attraction and invasion of whiteflies (*B. tabaci*), aphids (*A. gossypii*) and thrips (*Ceratothripoides claratus*), compared to UV-transmitting materials. Growing lettuce under UV-blocking materials decreased aphid density and the spread of aphid-transmitted viruses (Legarrea et al. 2012). Ben-Yakir et al. (2008a) reported that covering walk-in tunnels with OptiNet® reduced (three- to ninefolds) thrips infestations (mainly *T. tabaci*) compare with standard net of the same density. Preliminary results indicate that covering growing tunnels with UV-blocking plastic and OptiNet® significantly reduced the invasion by the chilli thrips as well (Ben-Yakir et al. 2012). Growing tunnels covered with a 40 mesh OptiNet® screen had significantly fewer onion thrips (fivefolds) compared with tunnels covered with a standard 50 mesh screen (Fig. 12.3). Also, tunnels covered with a 30-mesh OptiNet® screen had significantly fewer whiteflies (two- to threefolds)

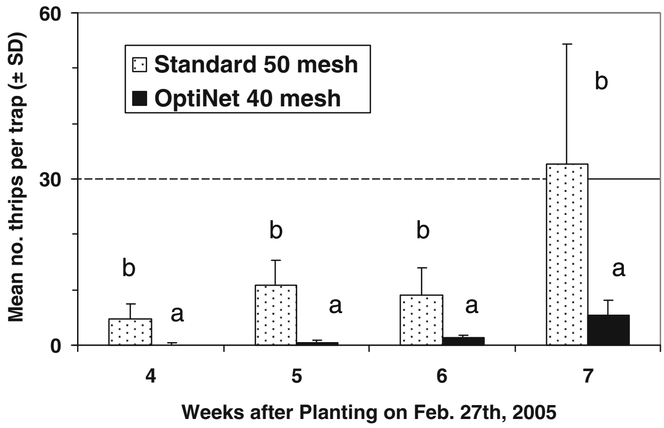

Fig. 12.3 The effect of photo-selective screen covering chives growing tunnels on the mean number of onion thrips (±SD) caught with blue sticky traps above plants. Besor. (N = 4)

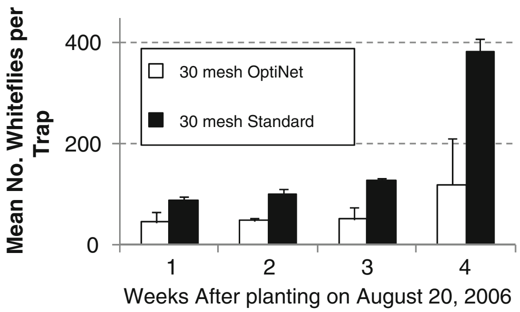

Fig. 12.4 The effect of screening with photo-selective additives on whiteflies infestation of tomato plants, Besor, 2006 (N = 4 tunnels/treatment; 2 traps/tunnel). On all weeks the bars are significantly different from each other at $P < 0.05$ (*t*-test)

compared to tunnels covered with a standard 30-mesh screen (Fig. 12.4). Thus, it is possible to use these nets at a lower density than 50 meshes without increasing the risk of pests' invasion. The use of nets with larger holes is expected to improve ventilation and to reduce heat stress. Both Bionet® and OptiNet® screens, which absorbed and reflected high amount of UV radiation, provided protection against thrips, whiteflies and broad mites on pepper (Legarrea et al. 2010).

The mechanisms by which Bionet® and OptiNet® provide protection against sucking pests have not been elucidated. Many researchers attribute the protection to evidence that sucking pests prefer UV containing environment and that under low UV they disperse at a slower rate than under high UV (reviewed by Johansen et al. 2011). However, optical cues are expected to be less important to locate host plants from a short distance because pests can use other senses (olfactory, tactile) for that purpose. On the other hand, as shown in the previous section (Sect. 6.1), OptiNet® reflects high levels of incident sunlight (about 30%) which deter pests landing. This mechanism has been overlooked and its role in the protection that Bionet® and OptiNet® provide needs to be further investigated.

Coarse nets are used in sub-tropical regions to protect crops from excessive solar radiation, wind, hail and birds, as well as for saving irrigation water. Traditionally, black shading nets have been used to cover crop plants. Colored (photoselective) shading nets are currently developed for improving crop production in addition to their roles listed above. The colored nets modify the spectral composition of both the transmitted and reflected sunlight. These nets also transform a large portion of the direct sunlight into scattered light. Recent studies have demonstrated that growing vegetables, fruits and ornamental crops under Red, Yellow, Blue, Grey and Pearl shading nets (ChromatiNets™, Polysack Plastics Industries, Nir-Yitzhak, Israel, http://www.polysack.com/index.php?page_id=46) increases their yields and improves their quality (Shahak et al. 2008). Preliminary studies indicated that the Yellow and Pearl nets protected crops from aphids and whiteflies but not from thrips (Ben-Yakir et al. 2008a; Shahak et al. 2009). The protection from aphids and whiteflies and the viral diseases that they transmit to vegetable crops was studied from 2006 to 2010 (Ben-Yakir et al. 2012). These studies were conducted in the semi-arid, Besor region, in southern Israel. The plants were grown in 'walk-in' tunnels (6×6×2.5 m) that were covered by various colored nets with 35% shading capacity. These nets have large holes that permit free passage of sucking pests that are only 1–2 mm in length. The average hole size for the Black, Red, Pearl and Yellow nets are 7×9, 5×7, 4×7 and 4×6 mm, respectively. We also found that whiteflies landed on the Yellow net 20–40 times more often than on the other nets (Ben-Yakir et al. 2008a; Offir unpublished). Despite that, the infestation levels of aphids and whiteflies in tunnels covered by either the Yellow or Pearl nets were consistently two- to threefolds lower than in tunnels covered by the Black or Red nets. The reduction in pests led to a similar reduction in the incidences of viral diseases they transmit. When the incidence of cucumber mosaic virus (CMV) in pepper grown under the Black or Red nets ranged between 35% and 89%, they were two- to tenfolds lower under the Yellow or Pearl nets. Similarly, when the incidence of the necrotic strain of potato virus Y (PVY) in tomato grown under Black or Red nets ranged between 42% and 50%, they were two- to threefolds lower under the Yellow or Pearl nets (Fig. 12.5). Also, when the incidence of tomato yellow leaf curl virus (TYLCV) in tomato grown under the Black or Red nets ranged between 15% and 50%, they were two- to fourfolds lower under the Yellow or Pearl nets.

The mechanisms by which Yellow and Pearl nets provide protection against aphids and whiteflies are not known. We propose that the optical properties of these nets play a major role in this protection. The sunlight transmission and scattering characteristics of these nets were reported by Shahak et al. (2004) and Rajapakse and Shahak (2007). The sunlight reflections of these nets are described in Fig. 12.6. Covering crops with shading nets may interfere with the ability of flying pests to see the host plants under the nets, and to discern the plants from their background. Since the threads of the light colored nets are more translucent than the black threads, light colored nets have higher density of threads than Black nets of the same shading capacity. Therefore, the light color nets probably block the view and hide the plants to a greater extent than the Black net. However, the Red net did not provide any protection from pests although its threads density is about twice as high as the

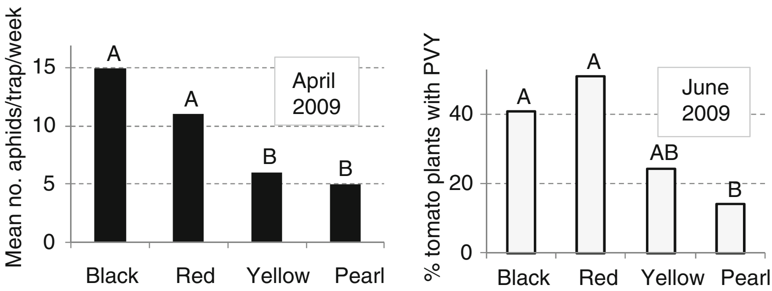

Fig. 12.5 The effect of colored shading nets on aphids' infestation and the rate of tomato plants with symptoms of PVY disease, Besor (N = 4 tunnels / net; 2 traps / tunnel; 70 plants / tunnel)

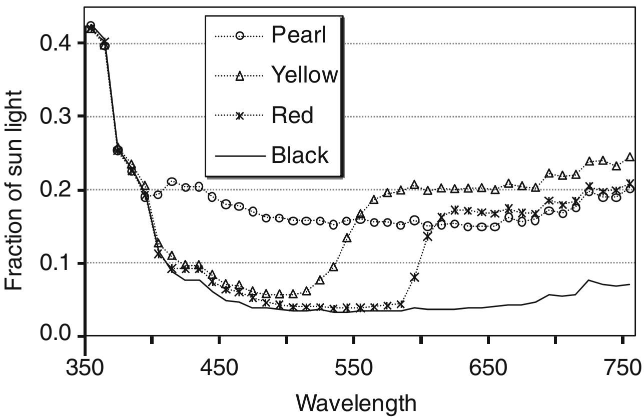

Fig. 12.6 Sunlight reflectance from colored 35% shading nets, Besor, 11:30 AM, December 10, 2007

Black nets. Therefore, hiding the crop plants does not seem to be a very important mechanism in the protection provided by the Yellow and Pearl shading nets. High reflection of sunlight deters the landing of both aphids and whiteflies (see Sect. 5). The reflection of sunlight in the range of 400–600 nm from Pearl nets is two- to fivefolds higher than that of the Black or Red nets (Fig. 12.6). Thus, the Pearl shading net can protect from pests by repelling them with its high glaring reflection. Yellow colored surfaces induce aphids and whiteflies to land, feed and settle (see Sect. 5). After the pests try to probe and feed in vain on the yellow plastic folia of the net, they usually fly away in what is termed a 'rejection flight' (Kring 1972). Thus, the Yellow shading net can protect from pests by attracting them away from the plants, delaying their entry to the growing area and, in turn, inducing them to fly away.

Similar protection from aphids and aphid-borne viral diseases was observed by Cohen (1981) in sweet pepper grown under coarse white, light grey or yellow nets in comparison to uncovered plants. The optical mechanisms that Cohen proposed included: (1) Interfering with the ability of pests to discern plants from their background, (2) Deterring landing by light colored nets, (3) Attraction of aphids away from host plants by the yellow net.

Floating crop covers are light weight synthetic fabrics that are placed over the plant beds after seeding for providing agronomic advantages to the plants grown under them. These covers can also protect plants growing under them from aphids and whiteflies and the viral diseases they transmit (Perring et al. 1989; Cradock et al. 2002; Qureshi et al. 2007). These covers provide physical barrier for pests but as they are usually colored white they probably also hide the plants and are highly reflective. Therefore, it is likely that the optical properties of the floating crop covers can contribute to their protection from sucking pests.

6.3 Optical Properties of the Host Plant

Characteristics of natural sunlight reflection from crop plants can affect the risk of infestation by pests. These include the reflected colors, visual patterns, contrasts and light intensity. The preference of onion thrips for specific varieties of white cabbage is determined, at least in part, by the differences in sunlight reflection between the head and the outer leaves (Fail et al. 2008). The preference of the cabbage seedpod weevil to various host plants is also related to the amounts of UV and yellow reflected from their flowers. The attractiveness of the flowers greatly increased when they reflected moderate UV and it decreased when they reflected low or high UV (Tansey et al. 2010). Visual assessment of onion cultivars indicated that those that were resistant to the onion thrips had yellow-green-colored foliage, whereas the susceptible cultivars had blue-green-colored foliage (Diaz-Montano et al. 2010). In curcubits, plants that have high pubescence that causes silvery reflection had a partial protection from aphids and aphid-transmitted viral diseases (Davis and Shifriss 1983). High reflection from crop plants for deterring pests can be produced artificially by spraying with highly reflective white kaolin-based particle film (e.g. Tsuchiya et al. 1995).

6.4 Elsewhere in the Growing Environment

Selectively modified light in the growing environment can disturb host finding by pests. An environment with low UV is not favored by sucking pests and it hinders their dispersal (see Sect. 5). Scattering and diffusion of light as well as enrichment of specific colors can reduce the contrast between host plants and their background. The Yellow and Pearl shading nets (described in Sect. 6.2) enrich the light passing through them with scattered and diffused light (Shahak et al. 2004). This may have also contributed to the protection that they provided against aphids and whiteflies.

Sticky boards and sheets with attractive colors are often placed near crop plants to divert pests away from the crop and to lower pest population by mass trapping. For example, in lettuce, mass trapping of the onion thrips and WFT with blue sticky cards provided significant protection from these pests (Natwick et al. 2007). Enhancing the reflection of colored traps with attractive light-emitting diodes (LED) has been demonstrated in several studies. Blue LEDs (peak emission at 465 nm) increased the trapping of WFT on blue sticky cards (Chen et al. 2004a). Yellow sticky card traps equipped with 530-nm lime green LED caught more whiteflies and leafhoppers (Chen et al. 2004b).

7 Future Research and Development

So far, optical manipulation of pests has been an unintentional byproduct of materials and methods that were developed for improving some aspects of plant production. We propose that optical manipulation of pests needs to be pursued as an independent topic for research and development.

Much information has been published about the visual response of aphids, whiteflies and thrips (see Sects. 4 and 5). However, more studies of pests' response to visual cues during migration, dispersal and host finding, in various agricultural environments, are required.

The optical manipulation proposed in this chapter is based on the use of reflected sunlight to interfere with host finding by sucking pests. This has been achieved already by using materials that are highly reflective, or materials that have attractive and camouflaging colors (see Sect. 6). However, currently the highly reflective materials used for covering crop plants are not selective enough and they block a significant amount of all the sunlight radiation. For example, Polyethylene sheets and nets containing the widely used UV blocking white pigment titanium dioxide are highly reflective (see OptiNet® reflection in Fig. 12.1). Therefore, currently used reflective covers increase shading and hinder plant development. Increased shading is particularly damaging for crops that are planted during the spring and fall. In those seasons, the intensity of sunlight is relatively low and the risk for infestation by sucking pests is very high. In the eastern Mediterranean, aphids and thrips are mostly abundant in the spring, and whiteflies are mostly abundant in the fall. Also, during the spring and fall plants are young and most susceptible to the viral diseases transmitted by sucking pests.

Plants mainly use the photosynthetically active radiation (PAR; ranging between 400 and 700 nm) of the sunlight. In general, sucking pests are most sensitive to radiation in the UV (330–350 nm) and in the green-yellow (520–550 nm) (see Sect. 4). Thus, covering material for optically manipulating pests should contain selective additives that let most of the PAR pass through and highly reflect the wavelengths that sucking pest can detect. The development of such selective additives will be a major advancement toward optically manipulating pests. Alternately, the highly reflective additives may not be distributed throughout the entire cladding materials but rather they will be limited to a few regions. For example, as a grid of reflective colored bands. Attractive colored materials may also be formed into attractive shapes over contrasting background and affixed on top of the cladding materials (e.g. yellow circles with a black ring around it). When the UV and the green-yellow portions of the sunlight are omitted from the growing environment it may negatively affect the performance of beneficial insects and mites that serve as natural enemies and pollinators. Here too, if the blocking additives or materials will be limited to a few regions of the covers it will alleviate the negative effect on the beneficials. To maximize the efficacy of optical cues, the reflective materials should face the sun at the peak time of pests' flight activity. Overall, covers designed for optical manipulation should be tailored to fit the specific crop, the major insect vector and the beneficial arthropods that are involved.

Inside protecting structures used for growing plants structural elements, boards or sheets, with attractive colors can be used for optical manipulation. Because these structures are densely packed with plants, non-visual senses can also be used by the pests to find their hosts. In protected crops, attractive optical cues may be enhanced by combining them with attractive odors, arresting glues or insecticides (attract and kill). Artificial lights may also be use to augment or to substitute the reflection of natural sunlight. Johansen et al. (2011) suggested using artificial light to attract and disrupt host-finding against whiteflies. In Japan they currently have a national research project entitled 'Elucidation of biological mechanisms of photo response and development of advanced technologies utilizing light'. Sucking pests like thrips and whitefly are being studied within the frame of this project. A team led by Dr. Masui, of the Shizuoka Research Institute of Agriculture and Forestry, is studying the effects of a single wavelength and mixed radiations on the behavior of *Thrips palmi* under laboratory and greenhouse conditions (Masui S personal communication).

Delay of sucking pests by arresting optical cues can be especially effective in protecting against stylet borne viruses such as CMV and PVY. These viruses must be transmitted within a short time (minutes to a few hours) after the aphids acquire them. Therefore, any delay of the infected aphids on arresting surfaces is expected to reduce the efficacy of viral transmission.

Some insects detect polarized light and are either attracted or deterred by certain types of polarization (Horváth and Varju 2004). The effects of polarized light on sucking pests need to be studied. Some plastics and glasses that are currently used for crop production change the polarity of sunlight and reflect polarized light to various degrees. This quality may also play a role in the optical manipulation of sucking pests.

8 Concluding Remarks

Manipulation of pests with optically modified cladding materials has been suggested by several authors (e.g. Doring and Chittka 2007; Antignus 2000). Pests may also be optically manipulated inside a greenhouse, using natural or artificial light, directly

(Reviewed by Johansen et al. 2011) or indirectly by affecting their host plants (Reviewed by Vanninen et al. 2010).

Reflecting natural sunlight to interfere with host finding by sucking pests has already been used in the form of reflective mulches. High reflection may be responsible in part for the protection from whiteflies and thrips by UV absorbing nets (see Sect. 6.1). Our recent studies show that pearl and yellow colored nets can also reduce infestations by aphids and whiteflies. Developing cladding materials that optically repel or arrest sucking pests is likely to be an effective strategy for plant protection. This technology could improve both crop production and pest management at the same time (Shahak et al. 2009).

The sunlight changes on seasonal and daily levels. Therefore, optical manipulation that is based on reflected sunlight may not very reliable method everywhere. In the Mediterranean region sucking pests are mainly active in open areas from March to October and during that period most days are sunny and clear. The reflective effect can be maximized if the reflective materials face the sun at the peak time of pests' flight activity.

It is unlikely that optical manipulation by itself will give sufficient protection for commercial crop production. Therefore, this technology should be integrated with other physical and chemical pest control methods. Optical manipulation can also be combined with varieties of crop plant that are less susceptible to viral diseases. The extra protection expected by the optical manipulation is likely to lower the infestation of sucking pests and reduce the viral diseases they transmit. This technology can help reducing the use of insecticides, which in turn, will slow down the development of insecticide resistance in whiteflies and thrips populations. Elucidating the mechanisms responsible for the plant protection by optical cues is likely to lead to the development of cladding materials that will provide a greater protection from sucking pests. The newly developed optically active materials must be compatible with optimal growing conditions. Materials and objects that optically repel or arrest pests can be important components of integrated pest management for both open field and protected crops.

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