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Western Flower Thrips (*Frankliniella occidentalis*) Management on Ornamental Crops Grown in Greenhouses: Have We Reached an Impasse?

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ABSTRACT

Western flower thrips, *Franklinella occidentalis* (Pergande) is considered the most destructive insect pest of greenhouse-grown crops due to direct feeding damage to plant parts such as foliage and flowers, and indirect damage by vectoring the tospoviruses; impatiens necrotic spot and tomato spotted wilt virus. Furthermore, western flower thrips (WFT) is difficult to manage in greenhouse production systems due to a number of factors including broad range of ornamental plants fed upon, high female reproductive capacity, rapid life cycle (egg to adult), residence in cryptic habitats such as unopened terminal buds that protect them from exposure to contact insecticides, and resistance to various insecticide chemical classes. As such, the management of WFT involves a holistic or complex approach including the concurrent implementation of scouting, cultural, physical, insecticidal, and biological strategies. Due to the lack of new insecticides being introduced for control of WFT, it is important that greenhouse producers preserve the longevity of currently existing products by establishing rotation schemes based on different modes of action. In addition, greenhouse producers must utilize sanitation and biological control practices to avoid solely relying on insecticides. The advent of resistance among WFT populations worldwide has led to a general interest among greenhouse producers in adopting the use of biological control as a long-term strategy to deal with WFT, and still produce and sell a quality crop.

Keywords: biological control, cultural control, pest management, resistance, sanitation, scouting

CONTENTS

INTRODUCTION

Greenhouse producers in the USA and worldwide are familiar with one of the most destructive insect pests of greenhouses: the western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). Western flower thrips (WFT) is the primary thrips species encountered by greenhouse producers and is extremely polyphagous, feeding on a wide-variety of horticultural crops grown in both commercial and research greenhouses (Brodsgaard 1989a; Gerin *et al.* 1994; Helyer *et al.* 1995; Tommasini and Maini 1995; Parrella and Murphy 1996; Lewis 1997a). This insect pest has been included in greenhouse pest control brochures since 1949; however, it was initially not considered a major insect pest of greenhouse-grown crops until the 1980's (Glockemann 1992; Jensen 2000; Brodsgaard 2004). This review paper has been developed to address a wide-range of topics associated with WFT including biology and damage, scouting, cultural and physical management, insecticidal management, resistance, and biological management. Furthermore, the current status of managing WFT in greenhouses and the issues discussed should provide insight on the importance of having to deal with WFT holistically instead of solely relying on insecticides.

BIOLOGY AND FEEDING DAMAGE

Knowledge of WFT biology and damage are important in understanding the challenges associated with developing a sound pest management program. Western flower thrips are small (approximately 2.0 mm in length) insects that possess piercing-sucking mouthparts (Chisholm and Lewis 1984;

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Invited Review

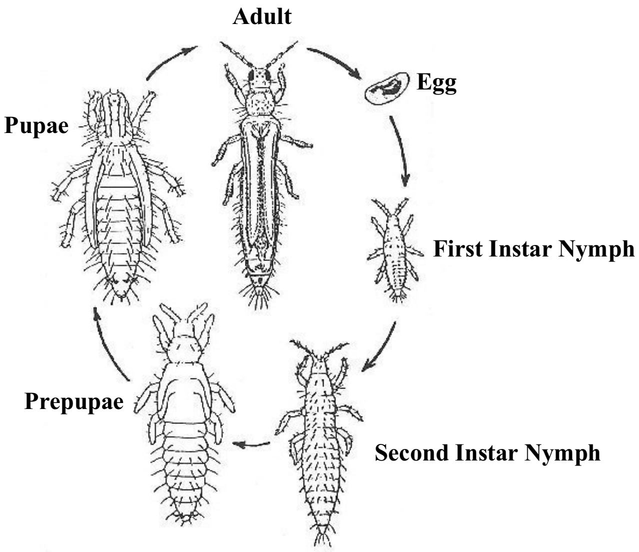

Fig. 1 Diagrammatic scheme of the life cycle (egg, two nymphal stages, two pupae stages, and adult) of the western flower thrips, *Frankliniella occidentalis* (Pergande).

Hunter and Ullman 1989). The life cycle consists of an egg stage, two nymphal stages, two pupal stages, and an adult (**Fig. 1**). In general, the life cycle (egg to adult) takes two to three weeks to complete (Robb *et al.* 1988; Ananthakrishnan 1993; Tommasini and Maini 1995; Mound 1996); however, development or the generation time from egg to adult is temperature dependent, with the optimum range between 26 and 29°C. Under these temperatures, the life cycle from egg to adult may be completed in seven to 13 days (Lublinkhof and Foster 1977; Robb *et al.* 1988; Gaum *et al.* 1994; Tommasini and Maini 1995). Females can live up to 45 days and lay between 150 and 300 eggs during their lifetime, primarily feeding on flower pollen, which may contain nutrients such as carbohydrates, proteins, sterols, and vitamins (Gerin *et al.* 1999) that enhance their development rate and reproductive ability (Trichilo and Leigh 1988; Brodsgaard 1989a; Oetting 1991; Higgins 1992). Western flower thrips may attack plants with elevated concentrations of nitrogen due to the abundance of amino acids and proteins, and female egg production is higher after feeding on plants containing abundant levels of amino acids (Ananthakrishnan 1993). Females typically lay eggs underneath the epidermal layer of the leaf surface, which protects them from exposure to contact insecticides (Lewis 1997a; Brodsgaard 2004), or in flower tissues. Eggs hatch in two to four days. The nymphs feed on both leaves and flowers (Thoeming *et al.* 2003). The first nymphal stage lasts one to two days while the duration of the second nymphal stage is two to four days (Robb *et al.* 1988). Second instar nymphs are typically more active and tend to feed more than first instar nymphs (Tommasini and Maini 1995). The second instar nymph eventually migrates to the base of a given plant and enters the growing medium to pupate (Thoeming *et al.* 2003). However, WFT will also pupate in leaf debris, on the plant, and in the open flowers of certain plant types including chrysanthemum (Fransen and Tolsma 1992; Jacobson 1997; Bennison *et al.* 2001; Broadbent *et al.* 2003). There are actually two "pupal" stages: a prepupae (or propupae) and pupae. Both stages commonly occur in growing medium or soil underneath benches (Arzone *et al.* 1989; Daughtrey *et al.* 1997). Growing medium or soil type and pH, and pupation depth may influence survival of the pupae (Varatharajan and Daniel 1984). Furthermore, pupation depth likely depends on the soil or growing medium type. The pupal stages do not feed and are very tolerant or immune to most insecticides commonly applied to manage WFT nymphs and adults (Tommasini and Maini 1995; Kirk 1997a; Seaton *et al.* 1997). Adults emerge from the pupal stage after approximately six days (Robb *et al.* 1988). Although WFT adults have wings, they do not fly very well, and may be dispersed throughout a greenhouse via air currents created by horizontal airflow fans (HAF) or wind entering from outside (Mound 1996; Daughtrey *et al.* 1997). Adults are attracted to certain flower colors (yellow, blue, and white), plant volatiles (*E*-β-farnesene), and flowering plant types (chrysanthemum, gerbera, marigold, and roses) (Walker 1974; Yudin *et al.* 1987; Vernon and Gillespie 1990; Kirk 1997b; Daughtrey *et al.* 1997; Terry 1997; Bennison *et al.* 1999; Bennison *et al.* 2001). Western flower thrips exhibit thigmotactic behavior meaning that the body is in constant contact with a surface, which is why they are located in secluded habitats on plants. This also protects them from exposure to contact insecticides (Tommasini and Maini 1995; Mound 1996; Jensen 2000; Brodsgaard 2004).

Western flower thrips have a haplo-diploid breeding system, which means that the females develop from fertilized eggs and males develop from unfertilized eggs (Moritz *et al.* 2004). Unmated females can produce males or sons parthenogenetically (without mating) whereas females must be mated in order to produce additional females or daughters (Bryan and Smith 1956; Higgins and Myers 1992; Heming 1995; Mound 1996; Moritz 1997). Female WFT may also mate with their own offspring. The sex ratio (females: males) is dependent on the population density with males tending to be more prevalent at "low" population densities whereas females are typically more abundant at higher densities. Increasing population densities of WFT in greenhouses enhances the probability of females encountering and mating with males immediately after emerging from the pupal stage. High population densities create an age structure consisting of young, fecund females producing a pre-dominance of daughters. However, as adult females age, they tend to produce more males (Higgins and Myers 1992).

Western flower thrips causes direct damage by feeding on plant leaves and flowers (van Dijken *et al.* 1994; Childers and Achor 1995). Although WFT has piercing-sucking mouthparts, they do not feed exclusively in the phloem sieve tubes. Instead they tend to feed on the mesophyll and epidermal cells of leaf tissues using a single stylet in the mouth and then inserting a set of paired stylets, which lacerate and damage cell tissues and function to imbibe cellular fluids (Mound 1971; Hunter *et al.* 1992; van de Wetering *et al.* 1996a). As a result, WFT feed on a multitude of food types within plants. Symptoms of WFT feeding include leaf scarring, distorted growth, sunken tissues on leaf undersides, and deformation of flowers. Flowers and leaves have a characteristic "silvery" appearance due to the influx of air after the removal of plant fluids (Chisholm and Lewis 1984; van Dijken *et al.* 1994; de Jager 1995). Black fecal deposits may be present on leaf undersides. Damage to plant leaves may also occur when females, using their sharp ovipositor, insert eggs into plant tissue (Jensen 2000). Furthermore, the wounds created by WFT during feeding or oviposition may serve as entry sites for plant pathogens such as fungi (Chisholm and Lewis 1984; de Jager *et al.* 1993; Tommasini and Maini 1995).

Western flower thrips, in addition, cause indirect damage by vectoring the tospoviruses: tomato spotted wilt virus and impatiens necrotic spot wilt virus (Allen and Broadbent 1986; Cho *et al.* 1988; Stobbs *et al.* 1992; MacDonald 1993; Daughtrey *et al.* 1997). The first and second instar nymphs acquire the virus, which is then transmitted by adults (Ullman *et al.* 1992; Ullman *et al.* 1993; Wijkamp *et al.* 1993, 1995; van de Wetering *et al.* 1996a, 1996b; Mound 1996; de Assis Filho *et al.* 2004; Moritz *et al.* 2004). Both direct and indirect types of damage may possibly result in an economic loss to greenhouse producers.

Distribution of infested plant material is one of the primary means of long-distance spread of WFT (Brodsgaard 1993; Kirk and Terry 2003). Western flower thrips is difficult to manage in greenhouses for a number of reasons including broad host range, high female reproductive capacity, rapid life cycle (egg to adult), small size (approximately 2.0 mm long), feeding habit, reside in cryptic habitats (unopened flower buds) and resistance to insecticides (Fery and Schalk 1991; Seaton *et al.* 1997; Jensen 2000; Thoeming *et al.* 2003). As such, the only way to effectively deal with WFT in greenhouse production systems is by taking a "holistic" approach via implementing a variety of strategies including scouting, and cultural and physical, insecticidal, and biological management (Jensen 2000).

SCOUTING

Scouting or monitoring is important in order to determine the numbers of WFT present in the greenhouse. Additionally, scouting will detect seasonal trends in WFT populations throughout the year and assess the effectiveness of management strategies implemented (Shipp and Zariffa 1991; Binns and Nyrop 1992). The main technique used to scout for WFT adults is to place either blue or yellow sticky cards above the crop canopy, although there is still disagreement on which color is the most attractive to WFT (Brodsgaard 1989b; Torres del Castillo *et al.* 1989; Mateus and Mexia 1995). The cards are counted weekly and the numbers of WFT adults are recorded (Gillespie and Vernon 1990). Visual inspection such as looking into open flowers, and/or shaking open flowers over a white sheet of paper are additional methods that may be used to scout for WFT nymphs and adults. Furthermore, gently blowing into open flowers will agitate WFT and increase their movement thus making it easier to observe them (Greene and Parrella 1992). However, a relationship between the numbers of WFT captured on colored sticky cards and the abundance of WFT present in flowers has not been established (Hsu and Quarles 1995; Jacobson 1997; Shipp *et al.* 2000). Greenhouse producers can establish their own "action thresholds" (the number of WFT detected either on colored sticky cards or visually that warrant the implementation of a pest management strategy) that they feel comfortable with. In a two-year greenhouse study, Cloyd and Sadof (2003) established an action threshold of 20 WFT adults per blue sticky card per week in a cut carnation (*Dianthus caryophyllus* L.) crop to determine the need for insecticide applications. Western flower thrips numbers, based on counts on the blue sticky cards from December through March for both years (1994 and 1995) were below the action threshold thus resulting in no insecticides being applied. This likely reduced the amount of "selection pressure" placed on the WFT population thus minimizing the prospect of resistance developing (discussed later). However, thresholds may vary from 10 to 40 WFT/sticky card/week depending on crop susceptibility to the viruses vectored by WFT (Frey 1993; van Dijken *et al.* 1994). Moreover, there are factors that may impact action thresholds via confounding or misleading sticky card counts including plant attractiveness, presence of flowers, placement of sticky cards, age structure of WFT population, migration of WFT into greenhouses, and crop growth stage. As such, the use of action thresholds may not be reliable in greenhouse production systems.

CULTURAL AND PHYSICAL MANAGEMENT

Sanitation practices such as removing weeds, old plant material and growing medium debris are the "first line of defense" in minimizing problems with WFT. Certain weeds, particularly those in the Compositae and Solanaceae families, and those with yellow flowers, not only attract WFT adults (Stobbs *et al.* 1992), but many weeds serve as reservoirs for the viruses transmitted (vectored) by WFT adults (Duffus 1971; Yudin *et al.* 1988; Bautista and Mau 1994; Chatzivassiliou *et al.* 2001; Kahn *et al.* 2005). As such, weeds must be removed from both inside and around the greenhouse perimeter (Cho *et al.* 1986; Nameth *et al.* 1988; Jacobson 1997; Brodsgaard 2004).

Furthermore, it is essential to immediately remove plant material debris from the greenhouse or place plant material debris into containers with tight-sealing lids since WFT adults will abandon desiccating plant material and may migrate onto the main crop (Yudin *et al.* 1988; Hogendorp and Cloyd 2006). Screening greenhouse openings such as vents and sidewalls will reduce populations of WFT entering greenhouses from outside or migrating into other greenhouses. The appropriate screen size or mesh for WFT has been demonstrated to be 192 µm (0.037 mm^2) or 100 mesh (Bethke and Paine 1991; Bethke *et al.* 1994). This may alleviate problems with WFT possibly moving from field-grown crops such as corn and soybean, and field-grown vegetables into greenhouses; however, this technique will not be effective if doors are continuously left open or if plant material already infested with WFT is moved among greenhouses.

Alternative cultural and/or physical management strategies that may be implemented include over-head irrigation or misting, which has been shown to decrease the abundance of WFT populations, by creating an environment less favorable for development (Lindquist *et al.* 1987); use of ultraviolet (UV) absorbing plastic films, which appear to influence WFT adult flight behavior by reducing the levels of ultra-violet light entering greenhouses (Costa and Robb 1999) or aluminized reflective fabrics that may inhibit or repel WFT adults from entering greenhouses (McIntyre *et al.* 1996); mechanically brushing plants, which has shown to reduce WFT damage in greenhouse-grown vegetables (Latimer and Oetting 1994); leaving greenhouses fallow (empty) for several months and heating for four to five days at 30°C (Lewis 1997b); and placing a weed fabric barrier underneath benches, thus preventing WFT from entering the soil to pupate (Cloyd RA, personal observation). Greenhouse producers can then routinely use mechanical blowers to distribute pupae (along with any plant and/or growing medium debris) into concentrated areas, which are then collected, and disposed of promptly. This may be one strategy to deal with this life stage in which there is no means of control.

Another strategy that may be helpful in managing WFT is the use of trap or lure crops (Hoyle and Saynor 1993; Pow *et al.* 1998; Bennison *et al.* 2001; Buitenhuis and Shipp 2006), which are plants (and flowers) that attract WFT away from the main crop. These plants and/or flowers may be sprayed with an insecticide, removed from the greenhouse, or inoculated with biological control agents such as predatory mites or predatory bugs (discussed later) that will feed on the nymph and adult stages residing in the flowers (Bennison *et al.* 2001). In our research, we have found that yellow Transvaal daisy, *Gerbera jamesonii* H. Bolus ex. Hook. f flowers are very attractive to WFT adults compared to other plant types and flower colors. Moreover, the reflectance spectra of yellow Transvaal daisy flowers are very similar to yellow sticky cards (Blumthal *et al.* 2005).

Although the inspection of incoming plant material from a supplier is often recommended before introducing into the main crop (Hsu and Quarles 1995; Parrella 1995; Jacobson 1997), this may be too labor intensive and time consuming, and not possible during the normal business hours of spring through early fall, especially after receiving large quantities of plant material.

INSECTICIDES

Since the tolerance for WFT damage on most greenhouse-grown ornamental crops is relatively "low" (Parrella and Jones 1987; Van Lenteren and Woets 1988; Brodsgaard 2004), the principal management strategy used to deal with WFT in greenhouses involves the use of insecticides (Parrella and Murphy 1996; Lewis 1997b; Herron and James 2005). The key to WFT management with insecticides is too initiate applications when populations are "low," which avoids dealing with different age structures or life stages – eggs, nymphs, pupae, and adults – simultaneously over the course of the crop production cycle. Once WFT populations' reach "high" levels, then more frequent applications at three to five day intervals may be required. Insecticides must be applied prior to WFT entering terminal or flower buds, as once they do, it is very difficult to obtain adequate control, and thus prevent injury. Insecticides with contact or translaminar activity are generally used to control or regulate WFT, because systemic insecticides typically do not move into flower parts (petals and sepals) where WFT adults normally feed (Daughtrey *et al.* 1997; Lewis 1997b; Cloyd and Sadof 1998). Those insecticides with translaminar activity, which means the material penetrates and resides in the leaf tissues forming a reservoir of active ingredient, provide residual activity even after spray residues have dried (Cloyd 2003). As a result, translaminar insecticides are more likely to be effective in killing WFT in terminal or flower buds. Applications conducted after flowers open are generally too late since damage has already occurred. High-volume sprays are typically required to reach WFT that are located in hidden areas of plants such as un-opened flower buds (Lewis 1997b).

Most currently available insecticides only kill the nymphs or adult, with no activity on either the egg or pupae stages (Seaton *et al.* 1997). As such, repeat applications are typically warranted in order to kill the life stages that were not affected by previous applications, such as nymphs that were in the egg stage and adults that were in the pupae stage (Lewis 1997b). This is especially important when overlapping generations are prevalent. Three to five applications within a seven to 10-day period may be needed to obtain sufficient mortality when WFT populations are "high" and there are different life stages (eggs, nymphs, pupae, and adults) and/or overlapping generations present (Heugens *et al.* 1989; MacDonald 1993; Seaton *et al.* 1997). However, frequent applications may lead to resistance developing in WFT populations (discussed later) and possible plant injury (MacDonald 1993; Jacobson 1997). Frequency of application depends on the time of year (season), as during cooler temperatures (winter) the life cycle is extended compared to warmer temperatures (spring through early fall), which will influence the number of applications required (Robb and Parrella 1995; Lewis 1997b). There are a variety of reasons for inadequate control of WFT with insecticides including spray timing, which is associated with the age structure of WFT populations; spray coverage; pH of spray solution; frequency of applications; and migration of WFT into greenhouses from outdoors (Cloyd RA, unpublished data). **Table 1** lists insecticides registered for thrips in the USA and their corresponding modes of action.

Spinosad

Spinosad is the active ingredient in the insecticide, Conserve® (Dow AgroSciences LLC; Indianapolis, IN), which has been the primary insecticide utilized by greenhouse producers in the USA to deal with WFT. This active ingredient has also been utilized worldwide under different trade names (e.g. Success® in Canada). The insecticide provided excellent control of WFT when it was introduced and commercially available for use in greenhouses in 1998 (Eger *et al.* 1998; Cloyd and Sadof 2000; Jones *et al.* 2002). However, since then, the level of control against WFT with spinosad has declined within the last few years (based on feedback from greenhouse producers), in all likelihood due to resistance (Jensen 2000). Spinosad is derived from a species of Actinomycete bacteria, *Saccharopolyspora spinosa*, which was discovered in the 1980's (Mertz and Yao 1990) that during fermentation creates metabolites called spinosyns; two are biologically active compounds, which are responsible for the insecticidal properties: spinosyns A and D (Kirst *et al.* 1992). Spinosad works quickly – killing WFT within one to three days after either contact or ingestion with up to two weeks of residual activity. Although the active ingredient may kill WFT on contact, it appears to work best when ingested. The mode of action involves excitation of the insect nervous system, leading to paralysis and death. Spinosad actually has two modes of action; disrupts the binding of acetylcholine at the nicotinic acetylcholine receptors located at the post-synaptic cell junctures, and negatively affects the gamma-amino butyric acid (GABA) gated ion channels (Salgado 1997, 1998). In fact, spinosad has a mode of action that is similar to the neonicotinoid-based insecticides (imidacloprid, thiamethoxam, acetamiprid, and dinotefuran) and macrocyclic lactone insecticide/ miticide (abamectin). However, spinosad acts or attaches to a different target site than either the neonicotinoids or the macrocyclic lactone (Thompson *et al.* 2000). Although spinosad has no systemic properties, it does exhibit translaminar movement through leaf tissue.

Spinosad, as mentioned above, was commercially available for use in greenhouses in 1998. As such, due to continual reliance of spinosad for control of WFT, certain populations of WFT in many states within the USA have demonstrated diminished sensitivity (or resistance) to spinosad. In fact, resistance may be more widespread than we think or know. It has been reported that populations of WFT in the USA are resistant to spinosad (Loughner *et al.* 2005) as well as populations in Australia (Herron and James 2005). Furthermore, in August 2008, Dow AgroSciences (Indianapolis, IN), which manufacturers spinosad, voluntarily sus-

Table 1 Insecticides commercially available and registered for thrips (including western flower thrips) in greenhouse production systems within the USA including common name (active ingredient), trade name, and mode of action. The numbers and/or letters in parentheses represent the Insecticide Resistance Action Committee (IRAC) mode of action group designations.

Active ingredient (common name)	Trade name	Mode of action
Abamectin	Avid	GABA chloride channel activator (6)
Acephate	Orthene/Precise	Acetylcholine esterase inhibitor (1B)
Azadirachtin	Azatin/Ornazin	Ecdysone antagonist (18B)
Bifenthrin	Attain/Talstar	Alter sodium channel gating mechanism (3)
Chlorfenapyr	Pylon	Oxidative phosphorylation uncoupler (13)
Chlorpyrifos	DuraGuard	Acetylcholine esterase inhibitor (1B)
Cyfluthrin	Decathlon	Alter sodium channel gating mechanism (3)
Fenoxycarb	Preclude	Juvenile hormone mimic (7B)
Flonicamid	Aria	Selective feeding blocker (9C)
Fluvalinate	Mavrik	Alter sodium channel gating mechanism (3)
Kinoprene	Enstar II	Juvenile hormone mimic (7A)
Methiocarb	Mesurol	Acetylcholine esterase inhibitor (1A)
Novaluron	Pedestal	Chitin synthesis inhibitor (15)
Petroleum oil	SuffOil-X/PureSpray Green	Suffocation (unclassified mode of action)
Pyridalyl	Overture	Unknown mode of action
Pyrethrins	Pyreth-It/Pyrethrum	Alter sodium channel gating mechanism (3)
Sorbitol octanoate	SorbiShield	Cuticle membrane desiccation and suffocation (unclassified mode of action)
Spinosad	Conserve	Nicotinic acetylcholine receptor agonist and GABA chloride channel activator (5)
Sucrose octanoate esters	SucraShield	Cuticle membrane desiccation (unclassified mode of action)

pended the sale and use of all spinosad-related insecticides in two counties in Florida (Broward and Palm Beach counties) due to positive identification that WFT populations had developed resistance to insecticides containing spinosad as the active ingredient (MeisterMedia WorldWide 2008). As such, in order to preserve or sustain the longevity of spinosad it is imperative that greenhouse producers rotate spinosad with other insecticides having different modes of action. It is important to note that spinosad is registered for use in a variety of agriculture crops in the USA under several trade names including Success®, SpinTor*, Tracer*, and Entrust® (for organic production). The potential consequences of this are that WFT, which migrate into greenhouses from field or vegetable crops, may have already been exposed to applications of agricultural formulations of spinosad thus increasing the potential for resistance being expressed rapidly when a greenhouse producer makes an application of spinosad.

The future value of spinosad depends on greenhouse producers. Currently, there are no new active ingredients that demonstrate the same or similar level of activity (based on percent mortality) on WFT as spinosad, so it is important that greenhouse producers avoid always using spinosad in order to reduce the "selection pressure" placed on WFT populations. The best way to avoid unintentional "selection pressure" is by scouting. The presence of only one adult WFT does not necessarily mean that adults are present throughout the crop. Only by installing and actually looking at either yellow or blue sticky cards regularly will greenhouse producers be able to determine when WFT adults are present. This will help avoid making applications when the age structure of the WFT populations are in a stage or stages such as eggs or pupae that are not affected by spinosad, which will save time and money.

New insecticides

Primarily due to the expense in developing new active ingredients and issues of resistance, there have been very few new products introduced to the market for management of WFT (Brodsgaard 2004); however, one new active ingredient became commercially available in 2009, and that was pyridalyl (Overture®; Valent U.S.A. Corporation; Walnut Creek, CA). This insecticide is labeled for both thrips (including WFT) and caterpillars, and is formulated as a 35WP (wettable powder) available in water-soluble packets. Pyridalyl is active as both a contact and stomach poison (Saito *et al.* 2004) although it has been proposed that contact activity may reduce WFT populations faster than ingestion. This insecticide, according to the label, has translaminar activity on a number of plant types including chrysanthemum, Transvaal daisy, hibiscus, and poinsettia. The product Overture® has a 12 hour REI (restricted entry interval), and the label rate for thrips is 8.0 ounces per 100 gallons. Furthermore, the product label specifically states that there should no more than three applications per cropping cycle or no more than three applications within six months. Based on our efficacy trials, pyridalyl does kill WFT adults with mortality ranging from 80 to 90% (Cloyd RA, unpublished data). It appears that pyridalyl is more toxic to second instar nymphs (2.8-fold) than adults (Isayama *et al.* 2005). One major difference between pyridalyl and spinosad is the speed of kill. Spinosad, in general, will kill WFT one to three days following application whereas pyridalyl takes at least seven days to kill a majority of WFT resulting in a delayed reduction in WFT populations when using this insecticide (Cloyd RA, unpublished data).

Alternative insecticides

There are two commercially available insecticides in the USA based on certain sugar components: SucraShield™ and SorbiShield™ (Natural Forces LLC; Davidson, NC). The active ingredient in SucraShield™ is sucrose octanoate esters whereas SorbiShield™ contains sorbitol octanoate as the active ingredient. Both products are labeled for control of thrips and are contact insecticides that either desiccate (by dissolving holes in the thrips cuticle or skin) or suffocate thrips. The active ingredient is an extract from the leaf hairs of wild tobacco (*Nicotiana gossei* Domin) plants (Neal *et al.* 1994). It should be noted that the restricted entry interval (REI) for SucraShield™ is 48 hours – yet it is permitted for use in organic production systems. We have evaluated both products for control of WFT, and have found minimal efficacy against the adult and nymphal life stages (Cloyd 2009; Cloyd RA unpublished data).

Resistance

The first instance in failing to manage WFT with insecticides was reported in 1961 when the chlorinated cyclodiene, toxaphene was not effective in controlling populations of WFT (Race 1961). Although since then there have been cases of reduced efficacy against WFT with insecticides, the first actual record of resistance occurred nearly 30 years later (Robb 1989). The sole reliance on insecticides to deal with WFT populations in greenhouses will eventually lead to populations developing resistance (Georghiou 1986). For example, certain WFT populations have been reported to be resistant to a number of chemical classes including organophosphate, carbamate, pyrethroid, and macrocyclic lactone (Helyer and Brobyn 1992; Immaraju *et al.* 1992; Zhao *et al.* 1994; Zhao *et al*. 1995a, 1995b, 1995c; Broadbent and Pree 1997; Kontsedalov *et al.* 1998). The main reason for this is that WFT has a haplo-diploid breeding system, which may accelerate the development of resistance. Haplo-diploid means that genes associated with resistance are fully-expressed in haploid (single set of chromosomes) males whereas with entirely diploid (double set of chromosomes) individuals resistance may be partially hidden as recessive or co-dominant traits (Denholm *et al.* 1998). The international trade of plant material may not only spread WFT populations but may also indirectly spread populations of WFT containing resistance genes or specific resistance mechanisms (Denholm and Jespersen 1998).

The primary way to prevent or minimize the potential of WFT populations from developing resistance and prolonging the effectiveness of currently-available insecticides is by rotating insecticides with different modes of action (Robb and Parrella 1995). However, rotating insecticides with variable modes of action will only be effective in delaying resistance if the insecticides applied select for different resistance mechanisms (Jensen 2000). In general, rotate different modes of action every two to three weeks or

Table 2 Examples of rotation schemes based on using insecticides* with different modes of action[z]. Each insecticide is applied once per week over a two-week period before a new insecticide with a different mode of action is used.

Spinosad (Conserve)	Chlorfenapyr (Pylon)	Abamectin (Avid)	Methiocarb (Mesurol)
Novaluron (Pedestal)	Pyridalyl (Overture)	Chlorfenapyr (Pylon)	Spinosad (Conserve)
Beauveria bassiana (BotaniGard/Naturalis/Mycotrol	Novaluron (Pedestal)	Acephate (Orthene)	Spinosad (Conserve)
Abamectin (Avid)	Pyridalyl (Overture)	Chlorfenapyr (Pylon)	Spinosad (Conserve)
Chlorpyrifos (DuraGuard)	Novaluron (Pedestal)	Abamectin (Avid)	Bifenthrin (Talstar)

* Trade names are those for the USA.
[z] Mode of actions of the designated insecticides: nicotinic acetylcholine receptor agonist and gamma-amino butyric acid (GABA) chloride channel activator (spinosad); oxidative phosphorylation uncoupler (chlorfenapyr); GABA chloride channel activator (abamectin); acetylcholine esterase inhibitor (methiocarb); chitin synthesis inhibitor (novaluron); unknown mode of action (pyridalyl); insect-killing fungus and unclassified mode of action (*Beauveria bassiana*); acetylcholine esterase inhibitor (acephate); acetylcholine esterase inhibitor (chlorpyrifos); and alter sodium channel gating mechanism (bifenthrin).

Table 3 Commercially available biological control agents for use in greenhouses worldwide against the western flower thrips, *Frankliniella occidentalis* (Pergande) and the target life stage.

Biological Control Agents	Target Life Stage of Western Flower Thrips
Neoseiulus (=*Amblyseius*) *cucumeris*	First instar nymph
Iphiseius (=*Amblyseius*) *degenerans*	First instar nymph
Amblyseius swirskii	First and second instar nymphs
Hypoaspis miles	Pupae
Orius insidiosus	Nymphs and adult
Steinernema feltiae	First and second instar nymphs
Beauveria bassiana	First, second instar nymphs, and adult

within a generation. However, this depends on the time of year since the development rate of the life cycle is temperature dependent. Again, **Table 1** lists insecticides Registered for thrips in the USA and their corresponding modes of action. **Table 2** provides examples of rotation programs involving insecticides commercially available in the USA with different modes of action.

BIOLOGICAL MANAGEMENT

Biological control of WFT relies on using natural enemies including the predatory mites *Neoseiulus* (=*Amblyseius*) *cucumeris* Oudemans, *Iphiseius* (=*Amblyseius*) *degenerans* Berlese, *Amblyseius swirskii* Athias-Henriot, *Stratiolaelaps* (=*Hypoaspis*) *miles* Berlese, and *Geolaelaps* (=*Hypoaspis*) *aculeifer* (Canestrini); the minute pirate bug, *Orius insidiosus* Say; the entomopathogenic or insect-killing nematode, *Steinernema feltiae* Filpjev; and the entomopathogenic fungus, *Beauveria bassiana* (Balsamo) Vuellemin. **Table 3** lists the commercially available biological control agents and their associated target life stage(s) of the WFT. In regards to the predatory mites, all regulate WFT populations by feeding on the first and/or second instar nymphs (Hessein and Parrella 1990) with the exception of *S. miles* and *G. aculeifer*, which are predatory mites that reside in either soil or growing medium feeding on the pupal stage (Gillespie and Quiring 1990; Brodsgaard 1996; Jacobson 1997). The use of "Black Pearl" pepper (*Capsicum annuum* L.) as banker plants is being utilized in certain greenhouses that are implementing releases of the minute pirate bug. Minute pirate bugs are predaceous anthocorid bugs that feed on the nymph and adult stages of the WFT (Baez *et al.* 2004; Brodsgaard 2004), and will consume pollen from the flowers as a supplemental food source.

There are a number of issues associated with using the entomopathogenic nematode *S. feltiae* against WFT including the cost of application, which is primarily dependent on the rates needed to regulate WFT populations, and mortality (number or percent of individuals in the population killed) obtained following application (Buitenhuis and Shipp 2005; Arthurs and Heinz 2006), which may be associated with formulation. Studies have demonstrated that the initial rates required to obtain sufficient control of WFT (≥80% mortality) are too expensive (Helyer *et al.* 1995). However, research is ongoing to deal with both issues so that greenhouse producers may eventually utilize insect-killing nematodes as a component of a rotation program.

The entomopathogenic fungus, *B. bassiana* has been used to manage WFT populations in cut flowers such as roses and carnations where the relative humidity is higher and more conducive for infection of WFT than on foliage where the possibility of desiccation is greater (Murphy *et al.* 1998). Adult WFT seem to be more susceptible to *B. bassiana* than the nymphs because adults tend to be located in flowers, where relative humidity is higher and conditions are favorable for infection. Moreover, nymphs appear to have a thicker cuticle than adults, which may delay penetration of the fungus into the body cavity, and the nymphs may also prevent penetration of fungal spores through the cuticle by shedding their exuvium (cuticle) during ecdysis (Vestergaard *et al.* 1995). However, infection is dependent on the concentration of spores (dose-dependence) that contact WFT nymphs and adults with a higher spore concentration leading to a faster and higher mortality rate (Brownbridge *et al.* 1994; Vestergaard *et al.* 1995; James *et al.* 1998), which may significantly reduce the abundance of individuals in future generations. Despite this, there are concerns related to the use of *B. bassiana* for regulating populations of WFT such as speed of kill, need for frequent applications, importance of thorough coverage of all plant parts, and low mortality levels obtained even under high relative humidities (Murphy *et al.* 1998; Shipp *et al.* 2003). For example, a relative humidity of 97.5% resulted in only 60% infection of adults and 43.9% infection of nymphs (Shipp *et al.* 2003). Furthermore, effectiveness of *B. bassiana* may be influenced by geographic location, which is affiliated with temperature and relative humidity, and possibly plant type (Ugine *et al.* 2005).

When implementing the use of natural enemies for regulation of WFT populations it is important to be aware of intra-guild predation, which is when one predator feeds on another predator when both are occupying the same habitat (Polis *et al.* 1989). This commonly occurs when generalist predators are used in biological control programs. For example, both *N. cucumeris* and *Orius* spp. will engage in intraguild predation under different cropping systems (Shakya 2005) and may feed on pollen more so than on WFT (Gillespie and Quring 1992), which will inhibit the regulation of WFT populations among greenhouse-grown crops.

Biological control of WFT, in general, can be very difficult or more challenging than using insecticides (Parrella 1995). However, the key to implementing a successful biological control program is to release natural enemies early enough in the cropping cycle. Releases must be initiated prior to WFT entering terminal or flower buds. Natural enemies will not regulate an already established or existing "high" WFT population because it takes time from release before natural enemies will lower WFT numbers below damaging levels. It is important to note that natural enemies will not "eradicate" (neither will insecticides) WFT. Biological control tends to work best on long-term crops like cut flowers or perennials more so than crops such as bedding plants, which typically have short production cycles (four to six weeks) (Brodsgaard 1995; Jacobson 1997). Another factor to consider is that biological control agents may not provide sufficient control (based on percent mortality) of the soil-dwelling life stages (pupae) to significantly impact WFT populations (Brodsgaard 1995; Jacobson 1995; Ebssa *et al.* 2001).

FUTURE STRATEGIES

The most recent development in an attempt to deal with WFT is the use of a sex aggregation pheromone lure (de Kogel and Teulon 2007). There are a number of companies that sell or distribute lures that are suppose to increase the number of WFT adults captured on sticky cards (in this case, blue) or attract WFT out of hiding places such as flowers or buds thus increasing their exposure to insecticide spray applications – resulting in higher mortality. In general, the pheromone lure is not a "control" device. However, there are still questions or issues associated with longevity of the scent within a greenhouse during certain times of the year and how effective the pheromone lure is when many different plant types are in flower. As such, further investigation is warranted on the potential usefulness of the sex aggregation pheromone lure.

SUMMARY

So, have we reached an impasse regarding the management of WFT? As this paper has indicated, WFT has been and is still a difficult insect pest to control or regulate in greenhouse production systems. As such, dealing with WFT requires a "holistic" or complex approach by diligently implementing scouting, cultural, physical, insecticidal, and/or biological management strategies. This includes proper sanitation practices, rotating insecticides with different modes of action, and releasing biological control agents early during the crop production cycle. These management strategies can reduce or regulate WFT populations to levels that will allow greenhouse producers to grow and sell a high-value quality crop with minimal aesthetic injury.

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