Management Strategies for Western Flower Thrips and the Role of Insecticides[1]

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1. Introduction

Today, the western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) is one of the most significant agricultural pests globally because of the damage it is able to inflict on a wide range of crops. Adults and larvae feed by piercing plant tissues with their needle-shaped mandible and draining the contents of punctured cells (reviewed in Kirk, 1997b). Feeding by adults and larvae produces scarring on foliage, flowers and fruits, which results in aesthetic crop damage and disrupts plant growth and physiology. Also, oviposition can produce a wound response in fruiting structures, which reduces the marketability of certain horticultural produce (Childers, 1997). Most importantly, western flower thrips is able to transmit several species of destructive plant viruses in the genus *Tospovirus* (Bunyaviridae). It is the most important vector of *Tomato spotted wilt virus* and *Impatiens necrotic spot virus* worldwide, and it is also known to vector Chrysanthemum stem necrosis virus, *Groundnut ringspot virus* and *Tomato chlorotic spot virus* (Pappu et al., 2009; Webster et al., 2011).

The actual amounts of economic losses attributable to any pest are difficult to determine, but Goldbach and Peters (1994) estimated that *Tomato spotted wilt virus* alone caused over US$1 billion in losses annually on a global basis. This estimate did not include the direct damage caused by western flower thrips, and it still would further underestimate present day losses, as the western flower thrips has continued to spread throughout the world (Kirk & Terry, 2003; Reitz et al., 2011). The state of Georgia, USA compiles estimates of the economic costs of pests to its crops. These estimates include both crop losses and the costs of control measures. From 2001 – 2006, costs from thrips and TSWV for tomatoes (*Solanum lycopersicum*) and peppers (*Capsicum annuum*) have averaged over 12% of the harvested value of those crops per year (Sparks, 2003, 2004, 2005, 2006; Sparks & Riley, 2001, 2002). Over 60% of the total for economic losses from pests and control costs in tomato and pepper are from thrips and tomato spotted wilt virus (Sparks, 2003). In addition, losses in Georgia

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in 2006 to ornamentals caused primarily by western flower thrips damage exceeded US$ 15 million. Clearly, these economic assessments show that the western flower thrips is one of the most destructive agricultural pests globally, but its emergence as a major pest has only occurred relatively recently.

The species "*Frankliniella occidentalis*" was first described as a member of the genus *Euthrips* by Theodore Pergande in 1895 from specimens collected in California, where its widespread distribution and abundance across many flowering plants was noted (Pergande, 1895). Subsequently, the species was described under several other names, which have since been synonymized (Mound, 2011). During the early to mid 20th century, the western flower thrips was regularly mentioned as a member of complexes of pestiferous thrips in western North America, but it was generally regarded as a less significant problem than species such as *Taeniothrips inconsequens* (Uzel), *Thrips tabaci* Lindeman, *Scirtothrips citri* (Moulton) and *Heliothrips haemorrhoidalis* (Bouché) (Moulton, 1931). For most of the early 20th century, western flower thrips remained a localized problem in California and other areas of the western USA and Canada, with sporadic problems reported from southern Texas to British Columbia.

One of the first cases of damage attributed to western flower thrips occurred on potatoes grown in the San Gabriel Valley of southern California. Feeding damage from large populations of the western flower thrips was implicated as the cause of curling of new foliage on potato *(Solanum tuberosum)*. The condition, termed potato curly leaf, would lead to significant reductions in tuber size and yield (Crawford, 1915). The recommended control for these thrips infestations was early season applications of Bordeaux mixture combined with extracts of tobacco, which was able to reduce losses when timed appropriately.

Also early in the 20th century, the western flower thrips was recorded as a pest of other vegetable, fruit and nut crops. Riherd (1942) observed oviposition damage on peas grown in the Rio Grande Valley of Texas, which reduced the aesthetic quality of fresh market peas (*Pisum sativum*). Similar spotting patterns, termed "pansy spots", on apples (*Malus domestica*) grown in the northwestern USA were attributed to western flower thrips oviposition (Childs, 1927; Moulton, 1931), as was damage to table grapes (*Vitis vinifera*) grown in California (Jensen, 1973; Yokoyama, 1977). Another significant type of damage to fruit crops resulted from feeding on floral tissues that would cause flower loss before fruit set. Occasionally, larval feeding was known to produce scarring of citrus fruit (Essig, 1926; Woglum & Lewis, 1935). During this period, western flower thrips also was implicated as one of thrips causing damage to alfalfa flowers (*Medicago sativa*), which reduced set seed (Borden, 1915; Seamaxs, 1923).

Later, during the 1950's the western flower thrips began to receive more attention as a pest of seedling cotton (*Gossypium hirsutum*) in the southwestern USA. Extensive use was made of all major classes of insecticides, including organochlorines, organophosphates, and carbamates, during the 1950's – 1960's, to combat this early season threat. Recommendations were made to growers to make multiple applications of insecticides to prevent loss of seedlings from thrips feeding damage. However, control failures with organochlorine insecticides were observed as early as 1960 (Race, 1961). The control failures with organochlorines then led growers to make preventative applications of organophosphates to protect seedlings. These were often made as systemic treatments at planting. However, Race (1965) recognized a significant disadvantage with this approach of intense preventative insecticide use, namely that growers could be making unnecessary applications when the

thrips populations did not warrant treatment. Further complicating management issues were the findings by Shorey et al. (1962) that carbamates actually led to rapid resurgence of western flower thrips populations after applications in cotton, which were likely related to adverse effects of the insecticides on beneficial insects.

Harding (1961a) observed that western flower thrips was the predominant thrips species infesting onions (*Allium cepa*) grown in southern Texas. It was also observed to be the predominant thrips in California onions (Hale & Shorey, 1965). Multiple applications of insecticides, predominately organophosphates, were found to reduce thrips abundance but not to improve yields significantly (Harding, 1961b).

Western flower thrips were noted as a minor pest of other vegetable crops in California. It was confirmed as a vector of *Tomato spotted wilt virus* in the 1930's (see Sakimura, 1962), but viral epidemics caused by western flower thrips apparently were not common at this time, and most damage was a result direct feeding rather than virus transmission (Sakimura, 1961). Similar to the situation with seedling cotton, western flower thrips feeding on young tomato plants was known to reduce photosynthesis and lead to defoliation and plant death (Shorey & Hall, 1963). Thrips feeding on lettuce (Latuca sativa) produces scarred, corky tissue on leaves. Shorey found that organophosphates would reduce populations for a short time after applications, but that populations would rebound soon after applications (Shorey & Hall, 1962). One of the causes identified for the lack of long term control of western flower thrips by insecticides in open field crops was that crops were subject to repeated ongoing dispersal of adults from outside crop fields (Shorey & Hall, 1963). Although tomato spotted wilt epidemics were uncommon in California at this time, Shorey and Hall (1963) also noted the inability of conventional insecticides to reduce Tomato spotted wilt virus transmission within fields because of the repeated dispersal of viruliferous thrips into fields from external sources.

Notably in major review articles concerning floriculture crops, western flower thrips was seldom discussed as a significant pest before the 1970's (Bryan & Smith, 1956; Naegele & Jefferson, 1964; Price et al., 1961), although the damage it caused to greenhouse-grown cut flowers was well recognized in California by the 1930's (Bohart, 1943). At this time, greenhouse growers relied on methods such as intensive sprays of nicotine sulfate or tartar emetic, and fumigation with nicotine, napthalene or calcium cyanide. Fumigation was found to kill adults but was far less effective against immature stages. Therefore, populations could rebound quickly after a fumigation treatment, thus exacerbating overall pest management concerns for growers.

2. Western flower thrips as an invasive species

It is likely that Naegele and Jefferson (1964) did not discuss western flower thrips because of its limited distribution at the time of their review article on floriculture pests. However, the pest status of western flower thrips began to expand rapidly in the late 1970's when growers in California began to experience more extensive damage to cut flower crops from thrips feeding and virus transmission (Robb, 1989). Because of the exceedingly low damage thresholds for these crops, growers responded to the threat with intensive insecticide treatments, leading to the rapid development of resistance to all major classes of insecticides available at the time, including pyrethroids, carbamates, organophosphates and abamectin (Immaraju et al., 1992).

This insecticide-resistant strain(s) of western flower thrips that originated in California is thought to then have spread around the world in association with the globalization of the cut flower and horticulture industries (Bonarriva, 2003; Huang, 2004). The western flower thrips was established throughout agroecosystems of eastern North America by the mid 1990's, and its spread through Europe was even more rapid (Kirk & Terry, 2003). It was first recorded in the Netherlands in 1983 (Mantel & Van de Vrie, 1988), and large outbreaks were observed in almost all European countries by 1990 (Kirk & Terry, 2003). In northern areas of Europe, western flower thrips is largely restricted to glasshouses[2] because climatic conditions prevent persistent populations from establishing (McDonald et al., 1997). In more southerly areas around the Mediterranean basin, populations have become established in open field crops, which facilitates the repeated colonization of protected crops (Brødsgaard, 1993; Kontsedalov et al., 1998). Since the distribution review by Kirk and Terry (2003), western flower thrips has continued to spread to new regions. Significantly, it is now a widely established pest in China (Reitz et al., 2011). As a reflection of its current cosmopolitan distribution and pest status, western flower thrips, a native of North America, is one of the most frequently intercepted insect species at USA ports of entry (Nickle, 2004).

Recently, the taxonomic status of *Frankliniella occidentalis* has been called into question. Molecular evidence indicates that "*Frankliniella occidentalis*" is a complex of two cryptic, sympatric species (Rugman-Jones et al., 2010). Rugman-Jones et al. (2010) have designated the two species as the lupin (L) and glasshouse (G) species. Neither of these genetic species corresponds to the historic morphological descriptions of the species of *F. moultoni* (Hood) or *F. occidentalis* (Pergande). The "lupin" and "glasshouse" designations are based on the similarity of certain individuals with a "western flower thrips" population that has been associated with *Lupinus arboreus* in New Zealand since the 1930's (Martin & Workman, 1994) and other individuals corresponding to pest strains found in European glasshouses (Brødsgaard, 1994). This recognition of species diversity within "*F. occidentalis*" adds uncertainty as to which species is under consideration in earlier literature. However, circumstantial evidence suggests that recent pest problems are largely the result of the highly invasive "glasshouse" type (Martin & Workman, 1994; Rugman-Jones et al., 2010).

Ironically perhaps, responses to these new, expanding problems from invasive western flower thrips populations were similar to historic control efforts attempted in the western USA; namely, there was a heavy reliance on insecticide use for control. Despite pervasive attempts to control western flower thrips with the widespread, intense use of insecticides, there are many factors that limit the efficacy of insecticides. These include ecological, behavioral and physiological factors, and these need to be appreciated and understood to place insecticide use in a proper context. Ecologically, western flower thrips is highly polyphagous and capable of reproducing on numerous host plants (Northfield et al., 2008; Paini et al., 2007). As large populations can develop on non-crop hosts, mass dispersal into crops occurs, whether open field crops (Pearsall & Myers, 2001; Puche et al., 1995; Ramachandran et al., 2001) or crops in protected environments (Antignus et al., 1996). The potential for continual recolonization of crops limits the observed field efficacy of insecticides (Eger et al., 1998; Reitz et al., 2003). This ongoing dispersal means that even repeated insecticide applications have little utility in reducing pest damage, especially in high value crops with low damage thresholds (Bauske, 1998; Kontsedalov et al., 1998). Once

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[2] The terms "greenhouse" and "glasshouse" are used interchangeably in this article for convenience, although they are not necessarily structurally equivalent.

having landed on plants, western flower thrips preferentially reside within flowers or other concealed, protected places on plants (Hansen et al., 2003; Kirk, 1997a). This thigmotactic behavior of thrips limits their exposure to many foliar applied insecticides. Also, the anthophilous nature of western flower thrips limits their exposure to systemic insecticides, which are not readily transported into floral tissues (Cloyd & Sadof, 1998; Daughtrey et al., 1997). Therefore, some of the most effective materials are those with translaminar properties, which increase the probability of thrips concealed in flowers actually ingesting toxins (Kay & Herron, 2010).

3. Insecticide use and insecticide resistance

While delivering toxins to western flower thrips can be problematic, and the species behavior and ecology can minimize exposure to insecticides, the species is well suited to evolve resistance to multiple classes of insecticides. Since the first reported case of control failures with insecticides (toxaphene, an organochlorine, Race, 1961), there have been numerous incidences of resistance reported to all major classes of insecticides from all regions of the world (Bielza et al., 2007b; Brødsgaard, 1994; Dağli & Tunç, 2007; Immaraju et al., 1992; Jensen, 2000a; Kay & Herron, 2010; Morishita, 2001; Robb et al., 1995; Weiss et al., 2009; Zhao et al., 1995). Resistance has not only developed against insecticides targeting western flower thrips, but also insecticides used to treat other pest species. Correspondingly, a number of different resistance mechanisms have been characterized to date, including metabolic detoxification, reduced penetration, altered target site resistance, and knockdown resistance (Bielza, 2008).

One class of insecticides where resistance problems have been particularly acute is the pyrethroids. Robb (1989) recorded control failures with pyrethroids in ornamental greenhouses in California. Management became so difficult, with a lack of alternative insecticides that growers returned to using legacy non-synthetic insecticides, such as nicotine sulfate. Despite these early reports regarding difficulties with pyrethroids, they have continued to be used against western flower thrips extensively, with the same outcome of resistance development (Broadbent & Pree, 1997; Espinosa et al., 2002b; Frantz & Mellinger, 2009; Immaraju et al., 1992; Seaton et al., 1997; Thalavaisundaram et al., 2008; Zhao et al., 1995). In these cases, the development of resistance to pyrethroids has tended to occur rapidly. Resistance to pyrethroids led Australia to abandon their use for western flower thrips management less than eight years after the pest was first detected (Herron & Gullick, 2001). Likewise, pyrethroids are no longer recommended for use in Turkish greenhouses because of the rapid development of resistance and cross resistance to other chemicals (Dağlı & Tunç, 2008).

Resistance to pyrethroids is primarily derived from metabolic detoxification pathways (Broadbent & Pree, 1997; Espinosa et al., 2005; Maymó et al., 2006; Zhao et al., 1995). A broad range of enzymatic detoxification pathways to detoxify pyrethroids have been identified, including cytochrome P450 monooxygenases, glutathione S-transferases and esterases. The predisposition of western flower thrips to evolve resistance based on metabolic detoxification is likely a product of its polyphagous nature. Because individuals move from host to host, they are likely to encounter a variety of plant defensive chemicals. Therefore, it is adaptive to have multiple means to contend with the unpredictable suite of host plant defenses that they may encounter (Rosenheim et al., 1996).

These inherent metabolic detoxification pathways predispose the western flower thrips to overcome pyrethroids and other classes of insecticides. Adding to the factors that make western flower thrips amenable to developing insecticide resistance are its rapid development rate so that populations may pass through several generations within a single cropping system, its high fecundity, so that resistant females can produce many offspring, and the haplodiploid sex determination characteristic of thrips (Reitz, 2009). In this type of sex determination, females are diploid, but males are haploid. Because males are haploid, their alleles are exposed directly to selection, which enable alleles for resistance to become fixed rapidly in a population (Denholm et al., 1998).

Insecticide resistance in western flower thrips is a complex phenomenon. It is important to note that resistance to a particular insecticide may not derive from a single trait and can involve multiple pathways (Jensen, 1998). For example, resistance to diazinon, an organophosphate, and methiocarb, a carbamate, has been linked to both metabolic detoxification and altered target site sensitivity (Jensen, 2000b; Zhao et al., 1994). In addition, distinct populations can evolve resistance to a particular insecticide through different mechanisms (Jensen, 2000b; Thalavaisundaram et al., 2008). However, a single metabolic mechanism may confer cross resistance between different classes of insecticides. Espinosa et al. (2002a) found that single metabolic pathway appears to confer resistance to pyrethroids and carbamates. In turn, Bielza et al. (2007a) proposed that such a single detoxification mechanism for the pyrethroid acrinathrin and for carbamates could be exploited, by using carbamates as synergists to increase the activity of acrinathrin through competitive substrate inhibition. These variable pathways complicate the prediction of resistance development and the potential for cross resistance to multiple classes of insecticides in any population.

Individuals carrying resistance alleles are often considered to be at a fitness disadvantage in a population when the particular insecticide to which they are resistant is not used (i.e., in the absence of particular selection pressures) (Georghiou & Taylor, 1986). When such a fitness disadvantage is present in resistant individuals, reversion to a susceptible population should occur soon after removal of the specific insecticide (selective pressure). However, this outcome may not always be the case for western flower thrips. There are cases of long term maintenance of resistance in the absence of insecticide exposure. Kontsedalov et al. (1998) reported that resistance to the pyrethroid cypermethrin did not decline after more than seven years of non-exposure for a laboratory colony. Likewise, resistance to organophosphates can be maintained in field and laboratory populations for several years without exposure (Brødsgaard, 1994; Robb, 1989). Bielza et al. (2008) compared fecundity, fertility, longevity, and egg-to-adult developmental time in populations of western flower thrips from Spain that were resistant and susceptible to acrinathrin (pyrethroid) and spinosad (a spinosyn formulation, see below), and found that resistance to either material did not carry significant fitness costs, at least in terms of the parameters they measured. Therefore, resistance may be expected to develop rapidly and be maintained for long periods of time in the absence of the use of an insecticide, and these scenarios must be taken into account in developing insecticide resistance management programs, which are integral to integrated pest management (IPM) programs.

Given the ongoing issues with management failures and resistance development with synthetic insecticides, and the cancellation of registrations for many other synthetic insecticides as a result of the Food Quality and Protection Act of 1996 (US EPA, 1996), there is a limited pool of efficacious insecticides for use against western flower thrips. Consequently, there is intense interest in developing new, alternative insecticides. Some of

the most efficacious insecticides against western flower thrips in recent years have been spinosyns, which are metabolites derived from fermentation of the actinomycete bacterium, *Saccharopolyspora spinosa* (Sparks et al., 1999). Spinosyns are in a group of insecticides with a novel mode of action, the nicotinic acetylcholine receptor (nAChR) allosteric activators (Group 5 – Insecticide Resistance Action Committee) (IRAC International MoA Working Group, 2011). The unique mode of action of spinosyn-based insecticides and their translaminar properties have made them highly effective against western flower thrips. The first products with spinosad as the active ingredient (a combination of spinosyns A and D; Dow AgroSciences, Indianapolis, IN) were registered for use in the late 1990's (Thompson et al., 2000). This was followed later by the release of spinetoram in 2008. Given the effectiveness of spinosyns and the lack of effective alternatives, growers tended to place an overreliance on spinosad, making them a victim of their own success. The first evidence of resistance to spinosyns was detected in western flower thrips populations in Australia by 2002 (Herron & James, 2005), Spain by 2003 (Bielza et al., 2007b) and the US by 2006 (Weiss et al., 2009). Spinosyn resistance in western flower thrips appears to be based on altered target site resistance, with spinosad resistance in a Spanish population based a single locus, autosomal recessive trait (Bielza et al., 2007c). The evidence that spinosad resistance is a recessive trait means that this resistance may not be stable, which would facilitate reversion to susceptibility in populations (Weiss et al., 2009). However, as with other resistance cases, mechanisms and genetics of spinosyn resistance likely vary across populations. Zhang et al. (2008) reported that spinosad resistance in a population from Japan is likely polygenic. Perhaps, more troubling is the potential cross resistance to other insecticides that Zhang et al (2008) found in their spinosad resistant strain. This potential will necessitate further caution in managing the use of spinosyn products.

In efforts to broaden the range of insecticides available for western flower thrips management, there has been interest in adapting other existing chemistries not previously labeled for use against western flower thrips. Neonicotinoids, which have been used since the 1990's to manage various types of other sucking insect pests, have recently received attention for a potential role in western flower thrips management. In experimental trials in Australia, Broughton and Herron (2009) found that two neonicotinoids, acetamiprid and thiamethoxam, were as effective as spinosad against larvae and adults of western flower thrips in pepper and lettuce. However, none of the tested insecticides, including spinosad, were effective in reducing the abundance of western flower thrips adults in tomato. Coutts and Jones (2005) found that drenching lettuce seedlings with neonicotinoids, in particular imidacloprid, just before transplanting reduced the incidence of tomato spotted wilt significantly in field trials. However, during their field trial, the predominant vector species were *Frankliniella schultzei* (Trybom) and *Thrips tabaci,* with very few western flower thrips found. Interestingly, their results showed that there were minimal effects of the neonicotinoids on the abundance of any of the thrips species. Likewise, western flower thrips populations showed little effect from applications of another neonicotinoid, dinotefuran, in pepper and strawberry (Dripps et al., 2010). It is possible that in these cases, mortality induced by the insecticide was counteracted by the loss of natural enemies of thrips from the insecticide applications. Alternatively, disease reductions observed by Coutts and Jones (2005) may have resulted from sublethal effects of the insecticides on thrips. Imidacloprid was found to actually enhance feeding of western flower thrips on tomato foliage while it reduced feeding by another TSWV vector, *Frankliniella fusca* (Hinds) (Joost & Riley, 2005). Likewise, the anthranilic diamide, cyantraniliprole, which disrupts

insect feeding activity, reduced TSWV transmission by *F. fusca,* but had no effect on transmission by western flower thrips (Jacobson & Kennedy, 2011). Therefore, more thorough evaluations should be made of the use of neonicotinoids specifically for western flower thrips management in different cropping systems. Given these results, it is important also not to extrapolate from the effects of insecticides on one thrips species, even congeneric ones, to *F. occidentalis.*

Despite indications of resistance to abamectin developing (Immaraju et al., 1992), it and related materials in the avermectin class have continued to receive interest as a means to manage western flower thrips in greenhouse and open field crops. Spiers et al. (2006) recently found that abamectin was as effective as spinosad in reducing western flower thrips feeding damage to gerbera daisies (*Gerbera jamesonii*). Overall flower quality was high not only because of the low amount of damage but also because of the lack of phytotoxic effects. The abamectin derivative, emamectin benzoate, has also been found to have efficacy against western flower thrips (Ishaaya et al., 2002). This material was found to be more potent than the parent material abamectin, and it was more effective against larvae than against adults. An advantageous property of abamectin and emamectin benzoate is that they are translaminar, increasing the likelihood that toxins will reach concealed thrips adults and larvae. However, other results have shown that these avermectins are not effective against western flower thrips in field trials (Kay & Herron, 2010). They found that their test population of western flower thrips was highly susceptible to abamectin and emamectin benzoate in direct exposure assays so that the field failures could result from difficulties in applying adequate doses of avermectins to plants in the field (Broughton & Herron, 2007).

Other newly developed insecticides with novel modes of action continue to be evaluated for their potential role in western flower thrips management. Pyridalyl, which has not been classified as yet for its mode of action, is more toxic to larvae than to adults of the western flower thrips, but it is compatible with biological control agents such the predatory bug *Orius strigicollis* (Poppius) (Isayama et al., 2005). This feature makes it an attractive insecticide for rotational use in an overall integrated pest management program. Pyridalyl is registered for greenhouse ornamentals in the USA and certain other crops elsewhere in the world. Likewise, the pyrrrol chlorfenapyr is registered for greenhouse ornamental and vegetables in the USA, but is approved for use in other situations globally. It has shown efficacy comparable to spinosad in greenhouse trials conducted in Australia (Broughton & Herron, 2009). Both pyridalyl and chlorfenapyr have translaminar properties. The systemic insecticide fipronil, a phenylpyrazole, is effective against western flower thrips larvae, and to a lesser extent, adults (Kay & Herron, 2010). In an interesting approach to synergizing insecticides, Cook et al. (2002) found that the addition of dodecyl acetate, a component of the western flower thrips alarm pheromone, increased the efficacy of fipronil in field trials against western flower thrips in strawberry (*Fragaria* × *ananassa*).

There has also been recent interest in the use botanically derived insecticides for use against the western flower thrips. Certain essential oils can help reduce the incidence of tomato spotted wilt in tomato (Reitz et al., 2008), and other *Chenopodium* based materials have shown efficacy under greenhouse conditions (Chiasson et al., 2004). *Chenopodium* based products, while not highly toxic under open field conditions, provide sufficient suppression of western flower thrips larvae to warrant inclusion in insecticide rotation schemes (Funderburk, 2009). These essential oil products tend to have little negative impact on natural enemies, so they may be compatible in overall IPM programs (Bostanian et al., 2005). One drawback in the use of plant essential oils has been that concentrations of oils needed to

have lethal insecticidal properties to pests can be phytotoxic (Cloyd et al., 2009, S. R. Reitz, unpublished).

There has been considerable interest in the use of microbial insecticides against western flower thrips (Butt & Brownbridge, 1997). Although experimental work has demonstrated the effectiveness of these materials and natural epizootics have been recorded (Vacante et al., 1994), there has been limited commercial success with them. Several products are available for commercial use (Shah & Goettel, 1999), and new formulations are still being developed (e.g., Zhang et al., 2009).

There has been a long history of insecticide use against the western flower thrips. Yet, there has only been a limited number of efficacious available at any given time, and none have been able to serve as a stand-alone management tactic. Although several new insecticides have been reported to have efficacy against western flower thrips, there is still a limited suite of insecticides that are effective. This limitation is likely to be an ongoing constraint because of the cost of developing and registering new insecticides. Therefore, to maintain the utility of efficacious insecticides as a part of IPM programs for western flower thrips, it is critical to take conservative and judicious approaches to the use of these insecticides.

4. Insecticide resistance management

Given the history of insecticide use against western flower thrips, resistance development is more than likely to occur to any insecticide, regardless of mode of action. Therefore, it is critical to develop strategies to employ them effectively. A key element in this regard is proper insecticide resistance management programs to maintain efficacy for as long as possible. In general, insecticide resistance management programs for western flower thrips do not differ conceptually from those designed for other pests. The basic concept is to rotate among insecticides with different modes of action at appropriate intervals to delay or inhibit the evolution of resistance within a pest population.

Most current insecticide resistance management plans recommend rotation of chemical classes after every generation of thrips (Broadbent & Pree, 1997; Herron & Cook, 2002; Robb et al., 1995). In Australia, the initial recommendations for insecticide resistance management were for growers to alternate among insecticides from different chemical classes with each application, a practice recommended in other regions (Funderburk, 2009). However, Herron and Cook (2002) proposed that this simple strategy would not be effective because of the long term persistence of resistance in populations to cypermethrin, a pyrethroid. They argued that reversion to a susceptible population would not occur before an insecticide was used again, rendering that material ineffective. It is also possible that alternating chemical classes too frequently (within a generation) could more readily select for individuals with resistance to multiple insecticides. In a subsequent study, Broughton and Herron (2007) advocated a three-consecutive spray program of a particular insecticide before rotating to a different chemical class. A key component to this strategy was that the three-consecutive applications needed to be made within a single thrips generation to gain the maximum effectiveness for that treatment.

The actual implementation of such an approach is limited by the continuous, overlapping generations present within a crop (Reitz, 2009), and may best be interpreted as rotating chemistries on an appropriate time interval (approximately 3 weeks). Bielza (2008) further cautioned that it is not simply enough to rotate among different chemistries. Rather rotation schedules should be based on known resistance mechanisms to avoid problems with cross

resistance. An example would be to rotate from chemistries in which metabolic resistance is likely to develop to chemistries in which target site resistance is likely to develop. The more types of resistance modes that can be built into a rotation plan, the more effective each material would be expected to be. Unfortunately in some cropping systems, growers may be faced with having only one or two efficacious classes of insecticides, which increases the risk of resistance development (Broughton & Herron, 2007). Many growers will make applications that are mixtures of more than one insecticides (Cloyd, 2009a). This is done either to combat more than one pest at a particular time, or in the belief that better control of a particular pest can be achieved with mixtures. However, Bielza (2008) also cautioned against using mixtures of insecticides because the structure of western flower thrips populations and resistance mechanisms may actually increase rates of resistance development when mixtures are used.

Bielza (2008) outlined a general resistance management protocol that also serves as a foundation for a sound IPM program. The four recommendations are to: 1) apply insecticides only when required; 2) make accurate and precise insecticide applications; 3) diversify the types of management methods that are used in a crop; and 4) conserve natural enemies. In addition, resistance monitoring needs to be conducted on an ongoing basis so that insecticides can be quickly removed from use before complete failures occur, and so that susceptibility to those materials can be restored. The proper stewardship of insecticide use will help to forestall the development of resistance in western flower thrips populations, as well as populations of other pest species inhabiting particular crops. Even with sound insecticide resistance management programs in effect, it is clear that insecticides cannot function as a stand-alone control method for western flower thrips, and most authors have advocated that insecticides not be used as a stand-alone management tactic. In fact, there cannot be a reliance on any single tactic, and truly integrated management approaches need to be employed.

5. Western flower thrips IPM in open field vegetables in the Southeastern USA

IPM programs developed in Florida for open field vegetable crops are an example of the evolution management programs for the western flower thrips and tomato spotted wilt virus. The development of these IPM programs has relied on a thorough understanding of western flower thrips biology and ecology. Perhaps, the most important aspect for successful management is the recognition that complete control of western flower thrips and elimination of damage is not attainable. Rather, the goal should be to manage thrips within acceptable limits that do not result in economically significant damage, and this goal has become the focus of current western flower thrips management programs (Funderburk, 2009).

Northern Florida, and the rest of the southeastern USA, is a major producer of fresh market tomatoes and peppers, although farms in this region tend to be relatively small (10 – 100 ha) and dispersed throughout the landscape (Bauske, 1998). Vegetable crops in the region are grown on beds covered with plastic mulches (Castro et al., 1993). Crops are started from transplants, with the typical crop growing in the field for 12 – 14 weeks. Tomato and pepper crops in the region did not experience pest problems from thrips until the western flower thrips invaded in the 1980's (Beshear, 1983; Olson & Funderburk, 1986). Initially, damage from western flower thrips was observed from oviposition and direct feeding of adults and

larvae on developing tomato fruits, which reduce their aesthetic quality and marketability (Ghidiu et al., 2006; Salguero-Navas et al., 1991). Similar scarring damage from feeding can occur on pepper fruit (Funderburk et al., 2009). However, soon after the invasion of the western flower thrips, epidemics of tomato spotted wilt began to occur throughout the southeast (Csinos et al., 2009) and crops remain at risk if proper management is not employed (Reitz et al., 2008). It is important to note that the most prevalent *Frankliniella* species in Florida and the southeastern USA are *F. tritici* (Fitch) and *F. bispinosa* (Morgan) (in southern Florida, Hansen et al., 2003), but these species do not cause the damage that western flower thrips do in vegetable crops.

The extensive crop losses caused by western flower thrips and *Tomato spotted wilt virus* have spurred considerable research to develop effective management programs. Understandably though, when western flower thrips and tomato spotted wilt first emerged as problems, tomato and pepper growers in the region responded with intensive insecticide treatments in attempts to prevent disease spread. By the 1990's growers in northern Florida were making an average of 16 separate applications of insecticides, with each application often being a mixture of multiple insecticides (Bauske, 1998). Despite such intense insecticide treatments, attempts at vector control through insecticides did not substantially reduce the problems. This lack of success results from the fact that most virus transmission in these crops is a result of primary spread of the pathogen – that is, infection comes from viruliferous individuals that disperse into the crop from external sources (Gitaitis et al., 1998; Puche et al., 1995). Furthermore, *Tomato spotted wilt virus* transmission occurs in as little as 5 minutes of an adult thrips feeding on a plant (Wijkamp et al., 1996). The following is a description of key pest management tactics that have been developed to successfully manage thrips and *Tomato spotted wilt virus* in open field fruiting vegetables.

5.1 Scouting

Because thrips species vary in their pest status, and because insecticides can differentially impact populations of native flower thrips and the invasive western flower thrips, it is necessary to accurately identify the species in order to make and evaluate management decisions. Thrips can be easily sampled by collecting flower samples into containers with alcohol. These samples can then be examined under a microscope with at least 40X magnification to determine the species. Various identification keys are available to assist with species identifications at this level (e.g., Frantz & Fasulo, n.d.). Periodic sampling can be used to assess shifts in the relative abundance of species of thrips throughout the growing season. When done systematically, this sampling is invaluable for determining the need for any insecticide application and the effects of such applications.

Sampling for crop management scouting purposes can be accomplished by counting the thrips from samples of ten flowers collected from each of several locations throughout a field. The number of samples needed to collect depends, in part, on field size. Because of the potential for scarring damage to fruit, it is also important to examine small, medium, and large fruits for thrips, with care taken to look under the calyx because of the thigmotactic behavior of thrips. Small fruits especially need to be inspected frequently as the eggs generally are laid during the flower stage, and larvae on the small fruit are the first indication of a developing problem. Again, it is important to sample fruit from several locations in each field.

5.2 Economic thresholds

Economic thresholds have been developed for thrips management in fruiting vegetable crops, including tomato, pepper and eggplant (Funderburk, 2009). These thresholds primarily apply to oviposition damage by female western flower thrips and to the feeding damage caused by adult western flower thrips and larvae of this and other thrips. Consequently, species identification in scouting is critical for the use of thresholds. Thresholds can guide growers for making therapeutic insecticide applications to mitigate these types of damage. However, growers must be aware that therapeutic treatments can do little to mitigate virus transmission. Therefore, preventative tactics must be employed to manage the primary spread of disease in crop fields. Secondary spread may be managed by scouting for larvae and treating, as appropriate.

Tomato: Although adults of all *Frankliniella* species that occur in Florida feed on pollen, petals and other floral structures in tomato, this feeding injury does not result in economic damage. However, once feeding by adults of western flower thrips and larvae of all species commences on immature fruits, it can produce "flecking" damage, which becomes apparent as the tomatoes ripen (Ghidiu et al., 2006). Oviposition in developing tomato fruit from western flower thrips also causes aesthetic damage (Salguero-Navas et al., 1991). Whereas 25 adults of native thrips (*F. tritici* and/or *F. bispinosa*) per bloom do not cause damage, one western flower thrips adult per flower is the threshold at which growers need to take action. An average of up to two larvae per small, medium or large fruit can be tolerated, but growers should take action at these thresholds (Funderburk, 2009; Funderburk et al., 2011).

Pepper and eggplant: As with tomato, adults of *F. tritici* and *F. bispinosa* cause little, if any, damage to pepper and eggplant, even with densities of 25 per bloom, and they beneficially outcompete western flower thrips and melon thrips, *Thrips palmi* Karny (Funderburk, 2009). Direct feeding damage from adults of western flower thrips and melon thrips is less severe than in tomato, and oviposition in immature pepper and eggplant fruit by western flower thrips does not cause the damage that is typical in tomato and some other crops. Therefore, higher thresholds can be tolerated in pepper and eggplant than in tomato. Up to six (6) western flower thrips and/or melon thrips adults per flower can be tolerated without damage. Once fruits begin to develop, growers need to be aware of scarring damage that adults of the western flower thrips and the melon thrips and larvae of all species may cause. Up to two larvae per small, medium, or large fruit on average in a field are tolerable. Growers should be prepared to take action if larval populations exceed two per fruit (Funderburk 2009). Because of the critical role that *Orius* spp. play in suppressing thrips populations and secondary virus spread, their populations should be monitored in scouting programs, and considered when assessing the need for insecticide treatments.

5.3 Biological control

Despite certain similarities between crops of tomato and pepper, there are fundamental differences in interactions between thrips and these two plant species. These differences mean that management programs must be designed for each crop. Adult western flower thrips readily colonize pepper and tomato (Baez et al., 2011). Tomato, though, is not a significant reproductive host for western flower thrips (Funderburk, 2009), but pepper can be a good reproductive host for these thrips (van den Meiracker & Ramakers, 1991). Consequently, there is the potential for secondary virus spread from within the crop (Gitaitis et al., 1998). However, Funderburk et al. (2000) demonstrated that the predator

Orius insidiosus (Say) colonizes peppers and can effectively suppress thrips populations in the crop (Funderburk et al., 2000; Ramachandran et al., 2001). In particular, *O. insidiosus* preferentially preys on western flower thrips over the native species *F. tritici* and *F. bispinosa* (Baez et al., 2004; Reitz et al., 2006). Therefore, conservation of these valuable naturally occurring biological control agents can significantly reduce pest problems in pepper and related crops (e.g., eggplant, *Solanum melongena*) and has become a cornerstone of IPM for pepper production (Funderburk et al., 2009). One of the keys to conservation of *Orius* species is to use insecticides that are minimally toxic to *Orius* spp., whether for thrips management or for management of other pests (Reitz et al., 2003). In contrast to pepper, *Orius* species do not have an affinity for tomato (Baez et al., 2011; Pfannenstiel & Yeargan, 1998), and so this naturally occurring biological control is not available for tomato.

5.4 Interspecific competition

Biotic limitations on western flower thrips populations can come from other species of thrips as well as predators, such as *O. insidiosus*. Recent studies have shown that interspecific competition from native thrips limits the larval survivorship of western flower thrips (Paini et al., 2008). In a survey conducted in northern Florida, Northfield et al. (2008) observed that over 75% of thrips collected from a range of uncultivated hosts were the native species *F. tritici*, with only 1% being western flower thrips. Similar results have been observed in crop fields where two-thirds or more of thrips in untreated or spinosad-treated pepper are the native species. Yet, the demographics differ in pyrethroid treated plots, where western flower thrips predominant (Hansen et al., 2003; Reitz et al., 2003). Because the native species *F. tritici* and *F. bispinosa* do not cause the economic damage that western flower thrips do, and because they outcompete western flower thrips, their conservation contributes to overall pest management. This difference in pest status among the species is why species identifications are an essential component of scouting in IPM programs.

5.5 Host plant location and ultraviolet reflective mulches

Thrips locate host plants primarily through a combination of visual cues, with anthophilous thrips tending to be attracted to colors of flowers. Western flower thrips are attuned to spectral radiation in the ultraviolet range (~365 nm) and in the yellow-green range (~540 nm) (Matteson et al., 1992). The yellow-green sensitivity is thought to play a role in long distance orientation to plants, and the ultraviolet sensitivity is part of the visual system to distinguish flowers. Anthophilous thrips, such as western flower thrips, are attracted to colors of flowers, especially white, blue and yellow flowers with low ultraviolet reflectance (Antignus, 2000). Therefore, increasing the reflectivity in ultraviolet range of the spectrum can repel thrips.

The ultraviolet reflective mulches available for the raised-bed plastic mulch production system of Florida are effective in repelling migrating adults of the western flower thrips, and this repellency reduces the primary and secondary spread of tomato spotted wilt. The use of ultraviolet reflective mulch also reduces the influx of the native thrips, *F. tritici* and *F. bispinosa*, but not disproportionately to reductions in western flower thrips (Momol et al., 2004; Reitz et al., 2003). Ultraviolet reflective mulches are most effective early in the crop season before the plant canopy begins to cover the mulch and reduce the surface area available for reflectance. Application of certain bactericides/fungicides and other pesticides also reduces the ultraviolet reflectance and hence the efficacy of the mulch. A single application of copper and mancozeb

for bacterial or fungal control can reduce the reflectance by nearly 50%. Repeated applications can consequently lead to higher incidences of tomato spotted wilt (S. R. Reitz, unpublished data). Therefore, using alternatives to copper and mancozeb early in the season for foliar pathogen management is advisable.

Ultraviolet reflective mulches also deter other pests, especially whiteflies and aphids, which can vector other plant viruses (Fanigliulo et al., 2009; Stapleton & Summers, 2002; Summers et al., 2010). Consequently, these materials are a good overall IPM tactic to employ where insect vectors are of concern. However, growers need to balance these benefits with the potential delay in plant growth in the spring because these mulches do not warm the soil as readily as standard black plastic mulches (Harpaz, 1982; Maynard & Olson, 2000). Newly developed mulches have helped to mitigate this effect by excluding the reflective metalized layer where transplants are placed.

5.6 Host plant fertilization

Soils in the southeastern USA tend to be nutrient deficient, so that growers need to add up to 200 kg of nitrogen per hectare (the recommended rate for Florida, Olson & Simmonne, 2009). However, growers have often overfertilized crops by up to 70% (Castro et al., 1993). This extra nitrogen fertilization can actually increase densities of western flower thrips. Female western flower thrips, in particular, preferentially settle on plants with higher nitrogen content (Baez et al., 2011; Brodbeck et al., 2001). This association seems to be most closely related to the phenylalanine content of tomato. From a pest management perspective, as vector populations increase with increasing fertilization there is an increase in the incidence of tomato spotted wilt. In north Florida tomatoes, the incidence of tomato spotted wilt was 50% lower for plants grown at recommended nitrogen levels compared with plants grown with supraoptimal nitrogen (Stavisky et al., 2002). Interestingly, *F. tritici* and *F. bispinosa* do not respond in the same manner to nitrogen fertilization as western flower thrips (Baez et al., 2011; Stavisky et al., 2002). Besides the increasing pest problems, excess nitrogen fertilization does not increase per plant yield. Therefore, growers can improve overall crop production of tomatoes and pepper by maintaining optimal fertilization levels.

5.7 Systemic acquired resistance

Many plants possess traits for systemic acquired resistance, which are induced defensive mechanisms against pathogens (Sticher et al., 1997). Certain chemicals have been found to stimulate these natural plant defenses against pathogens when applied to plants before infection occurs. Acibenzolar-*S*-methyl is a systemic acquired resistance inducer that stimulates the salicylic acid pathway for disease resistance in tomato and other crops. Commercial formulations of acibenzolar-*S*-methyl have been shown to reduce the incidence of tomato spotted wilt (Momol et al., 2004). Its use has minimal impacts on populations of the flower thrips. When tomatoes are grown on ultraviolet reflective mulches, Momol et al. (2004) concluded that acibenzolar-*S*-methyl provided little additional disease protection because of the large effect of the mulch. Nevertheless, acibenzolar-*S*-methyl is highly effective against bacterial pathogens that afflict tomatoes (Obradovic et al., 2005; Pradhanang et al., 2005), making it an excellent replacement for copper and mancozeb sprays on ultraviolet reflective mulches as well as standard black plastic mulch.

5.8 Host plant resistance

The single best defense against insect-vectored pathogens is host plant resistance. Numerous cultivars of tomato and pepper are resistant or tolerant to *Tomato spotted wilt virus* are currently commercially available (for a partial listing, see Funderburk et al., 2011). These cultivars have resistance to the virus, but not to thrips feeding or oviposition. All of the commercially available cultivars of tomato share a single source of resistance from the *Sw-5* gene. In pepper, all resistance is conferred by the *Tsw* gene. Both of the *Sw-5* and *Tsw* genes appear to be single dominant genes (Boiteux & de Avila, 1994; Stevens et al., 1992), and thus susceptible to being compromised by resistance breaking strains of the virus. In fact, such resistance breaking strains have commonly developed around the world (Roselló et al., 1996; Sharman & Persley, 2006). Presently in Florida, tomato spotted wilt resistant cultivars can maintain tomato spotted wilt incidences at economically acceptable levels. However, the threat of epidemics from resistance breaking strains is real. Coupled with the potential damage from western flower thrips feeding and oviposition, growers must maintain an integrated approach to thrips and tomato spotted wilt management.

5.9 Insecticides

Insecticides continue to have an important role to play in western flower thrips management. However, the use of insecticides must be done judiciously. Decisions regarding which insecticides to use and when need to be made in the context of both short-term and long-term management goals. Minimizing resistance development and avoiding the flaring of western flower thrips populations by their release from natural enemies need to be critical factors in insecticide use decisions. Populations of the invasive western flower thrips likely arrived in Florida with resistance to most classes of broad-spectrum insecticides (Immaraju et al., 1992). Further, flaring of the populations of the western flower thrips and other pests is possible when any broad-spectrum synthetic insecticide is used (Funderburk et al., 2000; Reitz et al., 2003). For this reason, growers are encouraged to move to newer, safer, and more selective insecticides in different chemical classes that are becoming available. Although growers are encouraged to use more selective materials when needed, the use of certain organophosphate and carbamate insecticides against western flower thrips may be warranted in certain circumstances. These should only be used in particular instances when nontarget effects would be minimal, for instance near the end of the production season to prevent scarring damage to fruit.

As discussed above, the most efficacious insecticides for western flower thrips, at present, are in the spinosyn class. No other insecticide class provides a similar level of effectiveness against western flower thrips. However, as resistance to spinosyns has been documented in Florida and elsewhere, limits are being placed on the number of applications that can be made in each crop to forestall further resistance development. A number of other insecticides are registered or in the process of being registered by the United States Environmental Protection Agency (EPA) that are able to suppress western flower thrips adults and larvae. Lists of currently available insecticides for western flower thrips management and their role in overall IPM programs for fruiting vegetable crops are available (Funderburk, 2009; Funderburk et al., 2011; Funderburk et al., 2009).

The fact that these materials are not as efficacious as spinosyns should not deter their inclusion in IPM programs. The focus of management should not be placed on killing the maximum number of thrips. Rather, the focus of management should be in minimizing damage below economically injurious levels. Because economic damage from oviposition

and scarring from feeding only occur at high levels (see above), even limited suppression of western flower thrips adults and larvae can maintain these types of damage well within tolerable limits. Secondary spread of tomato spotted wilt in tomato can also be limited by suppressing populations rather than attempting complete control (Momol et al., 2004). In pepper, conservation of *O. insidiosus* significantly reduces both primary and secondary spread of tomato spotted wilt (Funderburk et al., 2000; Reitz et al., 2003). We have found repeatedly that avoiding treatments that induce outbreaks of western flower thrips populations by killing natural enemies and competing species of native thrips within crop fields is an effective approach to minimizing losses to western flower thrips. Most broad-spectrum synthetic insecticides, including pyrethroids, organophosphates, and carbamates kill the native species of thrips that outcompete western flower thrips (Hansen et al., 2003; Reitz et al., 2003; Srivistava et al., 2008), leading to dramatic large scale shifts in thrips demographics (Frantz & Mellinger, 2009). These synthetic broad-spectrum insecticides not only can disrupt western flower thrips management, they also can disrupt management of other pests including spider mites, whiteflies, and leafminers, by eliminating natural enemies of those pests.

5.10 Vertical integration of the management program

One of the most important keys to successful crop production is not to consider problems in isolation. It is critical to understand how one management tactic may affect other production aspects. For example, in northern Florida, western flower thrips and *Tomato spotted wilt virus* are clearly the most important pest-complex facing tomato and pepper production. The use of ultraviolet reflective mulches has been effective in reducing populations of western flower thrips and the incidence of tomato spotted wilt (e.g., Momol et al., 2004; Reitz et al., 2003). Still, sweetpotato whitefly (*Bemisia tabaci* [Gennadius]) and whitefly-vectored viruses are occasionally important pests in northern Florida tomatoes (Momol et al., 1999). Ultraviolet reflective mulches used to manage thrips and tomato spotted wilt are also efficacious in reducing whitefly-caused damage (Antignus, 2000; Csizinszky et al., 1999).

In contrast, in southern Florida, western flower thrips and tospoviruses have only recently emerged as damaging problems requiring management consideration. Whiteflies and whitefly-vectored viruses have historically been the key insect pest and disease problems in tomato there. Growers use an wide range of insecticides to manage whitefly vectored viruses, particularly *Tomato yellow leaf curl virus*, which can devastate entire crops (Moriones & Navas-Castillo, 2000). Most tomatoes in southern Florida are treated with neonicotinoid insecticides at planting for management of immature whiteflies, with imidacloprid, thiamethoxam, or dinotefuran being most commonly used (Schuster et al., 2010). As the season progresses, growers may rotate "soft" insecticides, such as azadirachtin-based products, microbial insecticides such as *Beauveria bassiana* and insect growth regulators, into management programs against whitefly nymphs. While such materials are compatible with thrips management, they have little effect in suppressing primary virus transmission by whitefly adults that disperse into fields. As a result, growers still place a heavy reliance on broad spectrum insecticides, such as organophosphates and pyrethroids, for management of primary virus spread by whiteflies. The unintended consequence of this approach to whitefly management has been to release populations of western flower thrips from their natural controls, which greatly complicates overall crop management (Frantz & Mellinger, 2009; Weiss et al., 2009).

To facilitate overall crop management, growers are advised to anticipate key pests such as whiteflies or western flower thrips and to employ preventive tactics to minimize their impact. For tomato, one such preventative tactic would ultraviolet reflective mulches. It is also important from an areawide management perspective to maintain crop free periods and remove crops immediately after harvest so that crop residues do not serve as reservoirs for later infestations. In pepper grown in southern Florida, pepper weevil, *Anthonomus eugenii* Cano, is another significant pest. Its management also can be facilitated by crop free periods, and the destruction of crops immediately after harvest. Further sanitation, including the control of solanaceous weeds that serve as alternative hosts helps to reduce future populations. Using such preventative measures would minimize the need for insecticide applications for this pest. Consequently, there would be an overall benefit crop management because many of the available insecticides for pepper weevil management are pyrethroids or other disruptive broad spectrum synthetic insecticides. These are just some of the many pest problems that growers must contend with. Consequently, there is a clear need to integrate management programs for the diverse pests attacking crops. It is also critical to provide growers with realistic economic thresholds for different pests, and proper scouting techniques to assess pest abundances and the need, if any, to apply pesticides.

6. Conclusions and future directions

Only recently has the reliance on insecticides for western flower thrips management been challenged. Yet, failures to control western flower thrips with insecticides have become so severe that Cloyd (2009b) suggested we have reached an impasse in the use of insecticides against western flower thrips in ornamental greenhouse production and diverse management tactics must be employed. The successful management programs for western flower thrips and thrips-vectored viruses developed for solanaceous crops in Florida have been based on an understanding of thrips ecology and how different species interact with different crops (Funderburk, 2009). These strategies involve: an emphasis on scouting and the identification of thrips species present in a crop; the optimal nitrogen fertilization inputs to reduce the attractiveness of crops to western flower thrips without adversely affecting yields; the use of ultraviolet reflective mulches to deter thrips entrance into crop fields; the use of acibenzolar-*S*-methyl to suppress development of tomato spotted wilt symptoms in fruit of susceptible varieties; and the use of economic thresholds to determine the need and timing of insecticide applications; and the use of select insecticides to help suppress reproduction of thrips in the field, and thus manage secondary spread of tomato spotted wilt from within fields. The understanding of the importance of biotic resistance against western flower thrips provided by competing species of native thrips and natural enemies, such as *O. insidiosus,* has been of fundamental importance to improving western flower thrips management. This low input approach helps to avoid other pest problems as well. For example, the conservation biological control program for western flower thrips and *Tomato spotted wilt virus* in peppers has been used by growers in north Florida since the late 1990's, and growers have experienced far fewer problems from whiteflies, aphids, and other pests than when they were following a prophylactic, calendar-based spray program that included frequent use of broad-spectrum insecticides to control pests.

If western flower thrips were the only pest concern for growers, they would, perhaps, feel relieved. However, there are many other insect and pathogen threats to crops. We have now

begun to appreciate how management of one pest can interact with and affect management of other pests. Therefore, the need for sustainable, truly integrated pest management programs that do not consider individual pests in isolation is clear. There must be a focus on pest complexes rather than considering individual pest species. For example, insecticide resistance can be exacerbated when western flower thrips are exposed to insecticide treatments aimed at other pests (Immaraju et al., 1992).

The development of more selective insecticides that do not adversely affect natural enemies will improve overall crop management. These materials would reduce the risk of releasing non-target pests from control when treatments are necessary for another pest. Additional management tools that would reduce the need for insecticide applications will continue to be beneficial. Improved host plant resistance is one of those areas. The recent development of cultivars of tomatoes and peppers that show some degree of resistance to *Tomato spotted wilt virus* has eased concerns among growers. However, because the resistance conferred by the *Sw-5* gene in tomato and the *Tsw* gene in pepper is not durable, resistance-breaking strains can readily develop (Aramburu & Marti, 2003; Ciuffo et al., 2005; Latham & Jones, 1998; Margaria et al., 2004; Roggero et al., 2002; Thomas-Carroll & Jones, 2003; Thompson & van Zijl, 1995). In addition, virus resistance does not protect against physical damage. Therefore, it is still important for growers to maintain a multifaceted integrated management program.

Currently there are major research efforts underway to identify new germplasm sources of resistance to *Tomato spotted wilt virus*. One promising source of resistance appears to be the *Sw-7* gene from *Solanum chilense* (Price et al., 2007). Although this resistance is another single gene dominant trait, it is not linked to the *Sw-5* gene. Another exciting prospect for the future of host plant resistance is the identification of germplasm that is resistant to western flower thrips. Several accessions of different *Capsicum* species have been identified that have significant resistance against western flower thrips feeding (Maharijaya et al., 2011). If these traits can be incorporated into commercial cultivars, they may offer some degree of protection against virus transmission and aesthetic damage.

The management of western flower thrips will continue to be an ongoing challenge. Management programs cannot be static as they will need to be continually refined and updated with the advent of new invasive pests or as other conditions change. For example, *Scirtothrips dorsalis* Hood invaded Florida within the past five years and poses a threat to crops including pepper and eggplant. Recently, a new form of *Tospovirus,* a genetic reassortant of *Groundnut ringspot virus* and *Tomato chlorotic spot virus* has been found in Florida (Webster et al., 2010). Although western flower thrips can transmit this virus (Webster et al., 2011), it is not yet known if it or another thrips species is the most important vector. Despite these challenges, we believe that western flower thrips can be successfully managed, given a thorough understanding of its ecology and pest status.

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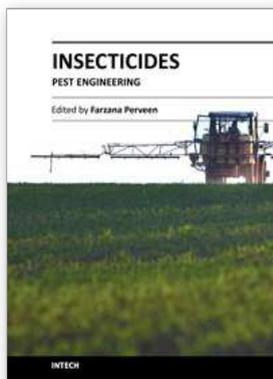
Insecticides - Pest Engineering

Edited by Dr. Farzana Perveen

This book is compiled of 24 Chapters divided into 4 Sections. Section A focuses on toxicity of organic and inorganic insecticides, organophosphorus insecticides, toxicity of fenitrothion and permethrin, and dichlorodiphenyltrichloroethane (DDT). Section B is dedicated to vector control using insecticides, biological control of mosquito larvae by Bacillus thuringiensis, metabolism of pyrethroids by mosquito cytochrome P40 susceptibility status of Aedes aegypti, etc. Section C describes bioactive natural products from sapindacea, management of potato pests, flower thrips, mango mealy bug, pear psylla, grapes pests, small fruit production, boll weevil and tsetse fly using insecticides. Section D provides information on insecticide resistance in natural population of malaria vector, role of Anopheles gambiae P450 cytochrome, genetic toxicological profile of carbofuran and pirimicarp carbamic insecticides, etc. The subject matter in this book should attract the reader's concern to support rational decisions regarding the use of pesticides.

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