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Insecticide Use and the Ecology of Invasive *Liriomyza* Leafminer Management

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1. Introduction

Leafmining flies in the genus *Liriomyza* (Diptera: Agromyzidae) are among the most economically important pests of vegetable and floriculture crops worldwide. Of the more than 300 species in the genus, approximately 24 species are economically important (Spencer, 1973). Among these, three species are of particular importance as crop pests. *Liriomyza huidobrensis* (Blanchard), *Liriomyza sativae* Blanchard, and *Liriomyza trifolii* (Burgess) are highly invasive species that have become established in agricultural areas throughout the world. These three highly polyphagous species cause extensive damage to a wide range of high value vegetable and floriculture crops. Other locally important members of the genus include *L. langei* Frick, which is a pest of ornamental and vegetable crops in coastal areas of California, USA (Parrella, 1982; Reitz et al., 1999); *L. bryoniae* (Kaltenbach), which is primarily a pest of glasshouse tomatoes in Europe (Smith, 1999), and of glasshouse and field crops in east Asia (Abe & Kawahara, 2001); and *L. chinensis* (Kato) which is a pest of *Allium* crops throughout Asia (Andersen et al., 2008; Chen et al., 2003; Spencer, 1990). Because these and other regionally important pest species share many of the same biological attributes and pest management challenges of the major invasive pest species, they too may become invasive pests of concern in the future. The following discussion of lessons learned from the three predominant pest *Liriomyza* species will help to provide information to minimize the threat of problems arising from other species and to avoid past mistakes. Ultimately, successful management of any of these species depends upon on development of comprehensive integrated pest management (IPM) strategies that address management of all pests in a cropping system.

Crop plants are damaged by *Liriomyza* by two means. The first form of damage is caused as females use their ovipositor to puncture the leaf surface to lay eggs and to create feeding

holes (Bethke & Parrella, 1985). The stippling patterns left from these punctures degrade the aesthetic value of ornamental plants, and sufficiently high levels of this puncture damage can reduce plant photosynthesis (Trumble et al., 1985). In addition, young seedling plants can be killed by intense puncture damage (Elmore & Ranney, 1954). Nevertheless, damage from female feeding and oviposition is generally minor in comparison with the more pronounced mining activity of larvae as they feed within leaves and stems of plants. Larval feeding not only reduces the marketability of plants because of the aesthetic damage, but it also reduces the photosynthetic capacity of plants, which reduces plant vigor, growth and yield (Al-Khateeb & Al-Jabr, 2006; Trumble et al., 1985). Sufficiently high densities of larvae can lead to defoliation. Leafminer caused defoliation can lead to significant losses in fruiting crops because the fruit becomes exposed to sunscald damage from the loss of the plant canopy (Schuster & Everett, 1983). On a per capita basis, *Liriomyza huidobrensis* has the most significant effect on host plants because it creates large mines in the spongy mesophyll of foliage and in petioles (Parrella et al., 1985). It is also known to mine pods of pea plants (*Pisum sativum* L.) (CABI, 2004). In contrast, *L. trifolii* and *L. sativae* tend to mine only through the upper palisade mesophyll of foliage.

In addition to the direct damage inflicted to crop plants, producers may suffer further economic losses because of quarantine restrictions that constrain international trade (Gitonga et al., 2010). Producers lose export markets when importing countries ban products because of the actual or potential presence of leafminer infestations in the country of origin. Even without complete bans, phytosanitary measures (e.g., fumigation or irradiation (Hallman et al., 2011)) required by importing countries may make exports cost prohibitive for producers in the country of origin.

2. Taxonomy, origins and invasiveness

One of the great challenges in understanding the pest status of *Liriomyza* spp. and effectively managing them has been the uncertainty regarding taxonomy and misidentification of pest species. Agromyzidae species occur throughout the world, and many species are morphologically similar, making distinctions among species difficult. Minkenberg (1988a) suggests that as a consequence invasive populations of *L. trifolii* became well established in some countries because specimens of early colonizers were misidentified as native species, and so no management programs were adopted. More thorough species determinations were not undertaken until widespread crop losses were reported by growers.

Among the three major pest species, there have been considerable historical problems with their taxonomy and identification. *Liriomyza sativae* was originally described from Argentina by Blanchard (1938) and is thought to be endemic to regions of South and North America (Spencer, 1973). It was recorded as a pest of numerous horticultural crops in southern Florida (USA) by the 1940s. Many early records of *Liriomyza* pests in Florida, USA refer to *Liriomyza pusilla* (Meigen) although the actual species of concern was almost certainly *L. sativae* (Spencer, 1973). *Liriomyza sativae* has probably been

present in California, USA since the early 20th century, but it is uncertain if the species that Oatman and Michelbacher termed *Liriomyza pictella* (Thomson) in a series of seminal biological studies (Oatman, 1959; 1960; Oatman & Michelbacher, 1958; 1959) was *L. pictella*, *L. sativae* or another undescribed sibling species.

The endemic range of *L. trifolii* is thought to encompass eastern North America, the Caribbean Basin, and parts of South America, although this range must be interpreted cautiously, again because of historical taxonomic uncertainty (Scheffer & Lewis, 2006; Spencer, 1965; 1973). Spencer (1965) noted that *L. trifolii* was widespread throughout Florida but did not consider it to be as significant of a pest as *L. sativae* at that time. The *L. trifolii* discussed by Frick (1959) as occurring in the western USA (California, Oregon, Washington) was later determined to be a new species, *L. fricki* Spencer (1965).

Liriomyza huidobrensis was first described, as *Agromyza huidobrensis*, from specimens reared from *Cineraria* in Argentina (Blanchard, 1926). For many years, *L. huidobrensis* was considered to be endemic to North America and to South America, although it was not recorded from Central America (Parrella, 1982; Spencer, 1973). In North America, this species was considered to be present in the far western states of the United States (California, Hawaii, Oregon, and Washington) (Spencer, 1973), but recent molecular research has confirmed that this North America taxon is a distinct species, *Liriomyza langei* Frick (Scheffer, 2000; Scheffer & Lewis, 2001).

Adding to the taxonomic complexity regarding *Liriomyza* is the recent discovery that *L. sativae* and *L. trifolii* are each composed of biologically distinct cryptic species (Scheffer & Lewis, 2005; 2006). There is evidence that other pest *Liriomyza* species may also be composed of biologically distinct cryptic species (Lonsdale, 2011; Morgan et al., 2000; Reitz & Trumble, 2002b). Genetic and ecological differences among such cryptic species have important implications for understanding the pest status and management of these species (Rosen, 1978; Scheffer & Lewis, 2005).

In addition to our evolving understanding of the taxonomy of *Liriomyza*, the history of *Liriomyza* spp. as pests has changed substantially over time. Although leafminers have been recognized as pests for many years, they remained relatively minor pests in limited geographic areas through the early 20th century (Hills & Taylor, 1951). In Florida, problems with leafminer control began to appear in the 1940s, which coincides with the advent of the use of synthetic insecticides (Hayslip, 1961; Wene, 1953). The initial species to cause these problems was *L. sativae* (Spencer, 1973). From the 1940s through the 1970s, there were repeated failures of insecticides to control leafminers in Florida (Hayslip, 1961; Levins et al., 1975; Wolfenbarger, 1954) and in the Rio Grande Valley of Texas (Wene, 1953), leading to substantial crop damage periodically. By the late 1970s, *L. trifolii* had become the predominant leafminer pest in Florida, and it soon became the most important pest of tomato (*Solanum lycopersicum* L.) in the state (Waddill et al., 1986). This sudden explosion of leafminer problems led growers to intensify insecticide treatments in attempts to manage the problems. Waddill et al. (1986) note that soon after the outbreak of *L. trifolii* growers were making three or more insecticide applications per week against leafminers with little success in managing the problem.

Although *L. sativae* was the predominant leafminer pest in California during the middle of the 20th century, it was not considered to be a major pest (Parrella, 1982; Trumble, 1981). Sporadic outbreaks of the species now recognized as *L. langei* did occur through coastal areas of California during the 1930s - 1950s (Elmore & Ranney, 1954; Frick, 1951; 1957; 1958; Lange, 1949; Lange et al., 1957). These outbreaks tended to be relatively short lived events, with *L. langei* reverting to a minor pest in between outbreaks. However, beginning in the mid 1990s sustained pest problems with *L. langei* emerged in coastal California (Heinz & Chaney, 1995; Reitz et al., 1999).

Liriomyza huidobrensis was not widely discussed as an important pest in South America until the 1970s (Chavez & Raman, 1987). The change in its pest status at that time has been attributed to insecticide induced outbreaks that resulted from intense insecticide treatments made against the primary pest of potato (*Solanum tuberosum* L.) in Peru, the leafmining moth *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). According to this hypothesis, constant exposure to insecticides for *T. absoluta* led to the evolution of resistance in *L. huidobrensis* populations, but the parasitoids that had contained *L. huidobrensis* populations were eliminated, creating classic secondary pest outbreaks (Luck et al., 1977). As a conclusion, the emergence of *Liriomyza* spp. as consistently important pests can be attributed to the selection for insecticide resistant populations.

In the mid 1970s, as more frequent and severe outbreaks of *Liriomyza* spp. began to be observed (e.g., Chavez & Raman, 1987; Leibe & Capinera, 1995; Oatman & Kennedy, 1976), leafminers began to emerge as globally important invasive pests of a wide range of horticultural crops. At this time, international trade in horticultural products (e.g., fruits, vegetables and cut flowers) began to escalate tremendously (Huang, 2004), which provided the opportunity for *Liriomyza* spp. to spread through the world on infested plant material (Minkenberg, 1988a).

Invasions of these *Liriomyza* spp. has continued unabated from the 1970s through to the present (Abe & Kawahara, 2001; Lei et al., 1997; Scheffer et al., 2006; Weintraub & Horowitz, 1995). All three of the major pest species now occur on all continents, except Antarctica. Even though the three major pest species share the common characteristic of being transported to new geographic areas via exported plant material, they have their own unique invasion histories. In many regions, more than one of the species has been introduced. These sympatric introductions have led to many complex interactions among the species, whereby one species is able to displace another previously established invasive species.

The introduction of *L. trifolii* into California, beginning in the late 1970s from plant material shipped from Florida brought the issue of invasive leafminers to the fore (Parrella, 1987). Soon after its introduction into California, *L. trifolii* displaced the previously established *L. sativae* as the predominant species in the state (Trumble & Nakakihara, 1983). To a large degree, this displacement appears to have resulted from the lower susceptibility of *L. trifolii* to commonly used insecticides (Palumbo et al., 1994; Reitz & Trumble, 2002a). The establishment of *L. trifolii* in California facilitated its spread to other countries, as infested propagation plants are shipped to production facilities in other countries. Then, final products are redistributed from these countries to yet other countries

(Minkenberg, 1988a). Today, *L. trifolii* is widespread throughout Europe, Africa and Asia. In the Americas, invasive populations have probably been introduced into regions where the species is indigenous (Minkenberg, 1988a).

Whereas *L. trifolii* has invaded many European countries, *L. sativae* has a more restricted distribution in Europe. It has been more widespread than *L. trifolii* in Asia and in Oceania, even though its presence was not recorded before the early 1990s. However, this distribution may be changing as *L. trifolii* invades more areas of Asia. For example, in the Chinese province of Hainan, *Liriomyza* spp. have been the predominant pest of cowpea, *Vigna unguiculata* L. Walpers, since 1993 when *L. sativae* first invaded the island and spread to other provinces. Subsequently, *L. trifolii* invaded Hainan in 2006, which has led to the displacement of *L. sativae* (Gao et al., 2011). In contrast to the displacements of *L. sativae* by *L. trifolii*, *L. sativae* appears to have recently displaced *L. trifolii* as the predominant species in Japanese vegetable crops (Abe & Tokumaru, 2008).

Liriomyza huidobrensis has spread rapidly through the world since the late 1980s when it was first recorded throughout Europe (reviewed in Weintraub & Horowitz, 1995). By the mid 1990s, it was well established throughout Asia, Africa and Central America (He et al., 2002; Scheffer et al., 2001; Shepard et al., 1998). It is not known at this time if *L. huidobrensis* has displaced either *L. sativae* or *L. trifolii* in any geographic region. Where these species co-occur, changes in demographics have been linked to climatic conditions, with *L. huidobrensis* predominating in cooler seasons or at higher elevations with cooler climates (Mujica & Kroschel, 2011; Tantowijoyo & Hoffmann, 2010; Weintraub, 2001a). Although *L. langei* has become a significant pest in California, it has not become an invasive species to date (Scheffer et al., 2001).

3. Biological influences on pest status

The pest status of *Liriomyza* spp. is closely tied to their biology. In part, their pest status results from the ability of populations of these flies to build up rapidly. Although there is considerable variation in the fecundity of *Liriomyza* spp. across studies, it is clear that females have a high reproductive capacity. For example, the mean fecundity for *L. sativae* females observed by Tokumaru and Abe (2003) was over 600 eggs per female. Although this may be an unusual observation, other studies routinely report fecundity in excess of 100 eggs per female. These species also have very rapid developmental rates, with a generation able to be completed in fewer than 20 days at optimal temperatures (Lanzoni et al., 2002; Minkenberg, 1988b; Parkman et al., 1989). Consequently, multiple, overlapping generations can be produced within a single cropping season. *Liriomyza sativae*, *L. trifolii* and *L. huidobrensis* are among the few members of the genus that are highly polyphagous. The host range of each species encompasses hundreds of species in a wide range of plant families (Spencer, 1990). This polyphagy allows populations of these species to develop on multiple crops, as well as uncultivated hosts, and then disperse into newly planted crops (Jones & Parrella, 1986; Trumble & Nakahihara, 1983; Tryon et al., 1980). Their polyphagy also presents many op-

opportunities for movement on plant material to new regions. As the eggs and larvae of *Liriomyza* spp. are concealed internally within plant foliage, they can be easily moved within shipments from production areas to final markets, and detection is difficult (Parrella, 1987).

4. Response to insecticides

One of the most important factors in leading to *Liriomyza* spp. becoming pests is their ability to evolve resistance to insecticides (Parrella & Keil, 1984). Leibee (1981) compiled a list of insecticides used against *Liriomyza* spp. in Florida and the life spans of their field efficacy in commercial use. The list of ineffective materials includes almost all classes of insecticides developed up to that time. Some insecticides became ineffective in as little as two years. This review confirmed the widespread importance of insecticide resistance in driving the pest status of *Liriomyza* spp. Despite the rapid failures of different insecticides, there has been a general belief, at least through the middle of the 20th century, that new chemistries would become available to replace ineffective ones, and provide a few additional seasons of control. Consequently, there was little emphasis on alternative management techniques until the advent of the worldwide leafminer crisis in the 1970s (Leibee & Capinera, 1995).

Intense insecticide use is the most common strategy used to eradicate newly discovered outbreaks of *Liriomyza* spp. (Bartlett & Powell, 1981). The success of this strategy is dependent on the susceptibility of invasive populations to available insecticides. Because invasive populations are already likely to be resistant to various insecticides (MacDonald, 1991; Parrella & Keil, 1985), eradication programs may not be successful.

Cross resistance to multiple classes of insecticides is also likely in *Liriomyza* spp. Despite a short history of pyrethroid use in Hawaii, high levels of tolerance to fenvalerate and permethrin were detected in field populations of both *L. sativae* and *L. trifolii* (Mason et al., 1987). The authors speculated that the tolerance/resistance arose as a result of cross-resistance to longer used organochlorine insecticides, which have a similar mode of action to pyrethroids. Populations of invasive *L. trifolii* obtained from greenhouses in Canada treated intensively with the organophosphate pyrazophos for less than 1 year showed high levels of resistance to that insecticide and to other types of organophosphates that had not been used previously (Broadbent & Pree, 1989). Fortunately from a pest management perspective, reversion to susceptibility to organophosphates and pyrethroids has been shown to occur within a few generations (within 1 year) (Broadbent & Pree, 1989; Parrella & Trumble, 1989). Interestingly, these Canadian populations showed no susceptibility to carbamates. It is possible that these populations were already resistant to carbamates and that laboratory-reared flies maintained their resistance for 5 years, or that carbamates are not toxic to *L. trifolii*.

At present, two of the most effective insecticides for *Liriomyza* management are abamectin and cyromazine. Both insecticides target the larvae inside the plant foliage. Cyromazine acts as a growth regulator; whereas abamectin is a neurotoxin that acts as a GABA agonist. Both have translaminar properties, allowing them to reach the larvae within the plant. Research by Schuster and Everett (1983) documented the effectiveness of both insecticides under field

conditions. Since that time, both have been commercially available. Despite this long history of use, resistance has not been a major problem in their use (Ferguson, 2004). The one recorded case of resistance to cyromazine cited in that study showed that reversion to susceptibility occurred within 8 generations in a laboratory strain and that field efficacy was restored within 2 seasons of reduced exposure.

Another class of insecticide with efficacy against *Liriomyza* spp. is the spinosyn class (spinosad and spinetoram). Spinosyn insecticides have been widely used since their introduction in the US in 1997. Similar to abamectin and cyromazine, spinosyns have translaminar properties, enabling them to target leafminer larvae. Spinosyns are neurotoxins also. However, they have a different mode of action than abamectin, one that disrupts nicotinic acetylcholine receptors (Salgado, 1998). Spinosyns are classified as Group 5 insecticides and abamectin is classified as a Group 6 insecticide by the Insecticide Resistance Action Committee (IRAC International MoA Working Group, 2011). There have been few reports of resistance to spinosyns to date among *Liriomyza* spp. (Ferguson, 2004). The lack of reported cases of spinosyn resistance may be considered surprising, given that spinosyn products are widely used against other key pests that co-occur with leafminers, including thrips and Lepidoptera pests (Demirozera et al., 2012; Reitz & Funderburk, 2012; Reitz et al., 1999). Incorporating the use of a penetrating surfactant improves the efficacy of spinosad against *Liriomyza* larvae (Bueno et al., 2007), allowing growers to improve management with lower rates of insecticide. This approach may also help reduce selection pressures. It is reasonable that increasing penetration of abamectin or cyromazine into plants would, likewise, increase their efficacy.

Selection of appropriate insecticides and rates for use in the field also depends upon proper identification of leafminer species. Parrella and Keil (1985) found that *L. trifolii* was much less susceptible to methamidophos than was *L. sativae* or *L. langei*. Likewise, *L. trifolii* populations in China are significantly less susceptible to abamectin and cyromazine than are populations of *L. sativae* (Gao et al., 2012). In contrast in Japan, *L. sativae* populations were less susceptible to several commonly used insecticides than were local populations of *L. trifolii* (Tokumaru et al., 2005). There is evidence that invasive populations of *L. huidobrensis* are more tolerant to certain commonly used insecticides than are sympatric populations of *L. trifolii* (Weintraub, 2001a).

5. Management trends

The premise that leafminers are secondary pests, which are released from natural control when their enemies are eliminated (Luckmann & Metcalf, 1994), has a long history, even if it has not always been fully appreciated. Studies dating back to the 1940s have shown the importance of parasitoids in maintaining *Liriomyza* spp. populations below economically damaging levels (Hills & Taylor, 1951) and where parasitoid populations are reduced in agroecosystems, there are outbreaks of *Liriomyza* spp. populations (Oatman & Kennedy, 1976; Ohno et al., 1999). Consequently, there has long been interest in identifying insecticides with low toxicity to *Liriomyza* parasitoids (e.g., Wene, 1953).

In every geographic region where *L. huidobrensis*, *L. sativae* or *L. trifolii* are indigenous, there is a rich complex of hymenopteran parasitoids (Liu et al., 2009). Parasitoid complexes associated with *Liriomyza* spp. generally consist of several species of larval and larval-pupal hymenopteran parasitoids. Many, but not all, of the species are oligophagous so that they may attack the different pest species and native non-pest *Liriomyza* spp. (Nicoli, 1997). It should be noted that there is evidence of differential parasitism across *Liriomyza* spp. Although, many parasitoids of *Liriomyza* are fairly generalized and are able to successfully attack various species, their reproductive success varies with the host (Abe et al., 2005). Still other parasitoids are not able to parasitize all *Liriomyza* species. This differential parasitism ability can have extreme implications for leafminer ecology. Greater levels of parasitism of *L. trifolii* than of *L. sativae* has been cited as one of the key factors in the displacement of *L. trifolii* by *L. sativae* in Japan (Abe et al., 2005; Abe & Tokumaru, 2008).

Parasitoids associated with native non-pest *Liriomyza* spp. have the potential to provide biological control of invasive leafminers because the native hosts serve as reservoirs for parasitoids populations (Chen et al., 2003; Nicoli, 1997; Tran et al., 2006). Often, parasitoids of *Liriomyza* pest species are introduced along with their alien hosts (Bjorksten et al., 2005; Tagami et al., 2006). These relationships may then be exploited as a form of unintended classical biological control.

Whereas parasitoids are valuable control agents, making effective use of them in practice can be challenging. Parasitoid populations, by their nature, will lag behind the development of their host populations (Hofsvang et al., 2005; Trumble & Nakakihara, 1983; Weintraub, 2001a). In these types of situations, growers may need to apply insecticides to keep growing leafminer populations below economically damaging levels. In a similar vein, growers may need to use insecticides to treat other pest problems, which then may have detrimental effects on leafminer management (Getzin, 1960). The outcome of either situation is that leafminer populations are released from their natural control and rapidly increase because many of the insecticides used against leafminers or other pests are highly toxic to their parasitoids. Should such a rapid increase occur growers are likely to believe that further insecticide treatments are warranted. This then becomes the very definition of the pesticide treadmill.

Most broad spectrum synthetic insecticides developed since the 1940s are highly toxic to parasitoids of *Liriomyza* spp. (Hidrayani et al., 2005; Oatman & Kennedy, 1976; Saito et al., 1996; Schuster, 1994). Classes of insecticides that have shown high toxicity to parasitoids include carbamates, organochlorines, organophosphates and pyrethroids, which are also insecticides that show limited efficacy against *Liriomyza* spp. (Hara, 1986; Hidrayani et al., 2005). Therefore, these types of insecticides should be used with great caution in systems where *Liriomyza* spp. are key pests. Several studies have shown that parasitoids are able to evolve resistance to insecticides under routine selection pressures in the field (Rathman et al., 1990; Spollen et al., 1995). Should parasitoids be resistant to a particular insecticide, that insecticide could be integrated into (IPM) programs. This would be especially true if the insecticide were targeting another pest species. However, to be effective, levels of resistance in the parasitoid population must exceed the field rate of the insecticide.

Of the three most effective insecticides for use against *Liriomyza* spp. today (abamectin, cyromazine, spinosyns), there have been variable conclusions regarding their effects on *Liriomyza* spp. parasitoids. Cyromazine is the least detrimental of these insecticides to *Liriomyza* parasitoids. As a growth regulator specific to Diptera, it does not directly affect the development of parasitic Hymenoptera. It does reduce the number of available hosts, and it will kill *Liriomyza* larvae before parasitoids may complete their development. However, these effects should complement the action of parasitoids to enhance overall management of *Liriomyza* pests.

Results of various studies provide conflicting results for the effect of abamectin on leafminer parasitoids (reviewed in Kaspi & Parrella, 2005). In general, field studies have demonstrated that abamectin and spinosyns are not as detrimental to parasitoid populations as carbamates, organophosphate or pyrethroids, but they are more deleterious than cyromazine (Priyono et al., 2004; Schuster, 1994; Trumble, 1985). The greater toxicity of abamectin and spinosyns compared with cyromazine to *Liriomyza* spp. parasitoids have been demonstrated in laboratory studies (Babul Hossain & Poehling, 2006; Bjorksten & Robinson, 2005). In particular, abamectin and spinosyns are lethal to parasitoid adults. Interestingly, parasitoid populations may rebound faster in abamectin treated fields compared with cyromazine treated fields, a result attributed to the longer residual period of cyromazine (Weintraub, 2001b). These results clearly show that insecticide use should be approached cautiously and that growers should be encouraged to consider the costs and benefits of different insecticide uses.

In recognition of the importance that parasitoids play in managing leafminers, Trumble and colleagues initiated development of IPM programs for field grown vegetables in California and Mexico. One of the first aspects addressed in the research program was to establish realistic economic thresholds in these agroecosystems for the key insect pests, *L. trifolii* and the beet armyworm, *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae) (Reitz et al., 1999; Trumble, 1985; Trumble & Alvarado-Rodriguez, 1993; Trumble et al., 1997). According to program guidelines, when systematic sampling shows pest populations exceeding economic thresholds, growers would select an insecticide to bring the populations under damaging levels. The key to maintaining stable management of *Liriomyza* spp. rests in selecting insecticides that are the least disruptive to the leafminer parasitoid complex.

In commercial scale trials conducted in celery (*Apium graveolens* L.) and tomato, these IPM programs were compared with conventional high input management programs. Insecticides for the IPM programs consisted of *Bacillus thuringiensis*, tebufenozide (an insect growth regulator) and spinosad for management of Lepidoptera, and abamectin and cyromazine for *Liriomyza* management (Reitz et al., 1999; Trumble & Alvarado-Rodriguez, 1993; Trumble et al., 1997). To minimize the risk of insecticide resistance, growers are encouraged to rotate abamectin and cyromazine, should multiple applications be needed in a crop. The conventional, high input management programs reflected standard grower practices of the time and included weekly applications of broad spectrum synthetic insecticides, including methomyl (carbamate), permethrin (pyrethroid) and methamidophos (organophosphate).

These trials consistently showed that the IPM programs had consistently lower populations of *Liriomyza* spp. than the high input conventional programs. These results were seen because the IPM programs were able to conserve the leafminer parasitoids. More importantly for growers, because insecticide applications in the IPM programs were based on scouting results and linked to economic thresholds, fewer insecticide applications were made in the IPM programs than in the conventional programs. By focusing on conservation of leafminer parasitoids, growers can reserve use of the few highly efficacious insecticides for situations where there is a danger of leafminer population outbreaks. Limiting their use to these situations mitigates the risk of resistance developing to these insecticides.

Despite the lower insecticide use, growers were not sacrificing the amount of crop harvested or its quality. Ultimately, these IPM programs based on economic thresholds with the goal of conserving *Liriomyza* spp. parasitoids enable growers to produce high quality crops at lower cost and with typically greater profit than programs with higher insecticide inputs. By including economic comparisons of management programs, these trials provide growers with an economic rationale to alter their management methods (Reitz et al., 1999).

Liriomyza spp. management in protected environments, such as enclosed glasshouse and greenhouse production systems, generally requires greater inputs than for field grown crops. Greenhouses are highly managed environments where growers have extensive control over crop conditions (Shipp et al., 1991). Yet, given the potential value of crops and the high production costs, many growers produce crops year round without periods to sanitize facilities. This continuous production is conducted at optimal temperatures for plant and, consequently, insect development. Therefore, the greenhouse environment is highly conducive to the development of pest populations, but colonization by naturally occurring beneficial organisms is restricted. With the lack of naturally occurring biological control available to most greenhouse systems and the high crop value, growers historically relied on intensive insecticide use for pest management, and this reliance on insecticides has hindered the development of IPM programs for greenhouse production (Parrella & Jones, 1987). Further complicating adoption of IPM programs in greenhouses are the exceedingly low damage threshold for floriculture and vegetable crops that are grown in protected environments (Yano, 2004).

Despite these constraints, there have been successful demonstrations of integrated management of *Liriomyza* spp. and other pests in greenhouse systems. The initial impetus for development of IPM programs has, not surprisingly, been the development of resistance and failure of insecticides to effectively manage pests. IPM programs for greenhouse systems have been widely adopted in northern and western Europe (van Lenteren, 2000). There, natural enemies are commercially available for all major pests, including parasitoids in the genera of *Dacnusa*, *Diglyphus* and *Opius* for *Liriomyza* management. These parasitoids can be released augmentatively and become established in greenhouses for long term management of leafminers. Because of the high demand for natural enemies to meet the needs of the large European greenhouse industry, mass produced natural enemies are cost effective for European growers to use. However, while augmentative biological control with parasitoids in the United States and other non-European countries has been shown to be effective in man-

aging *Liriomyza* populations, to date, it has not been as economically cost effective as the judicious use of insecticides (Chow & Heinz, 2006; Ozawa et al., 2001). These economic differences make growers less likely to adopt insecticide alternatives

An ideal insecticide for incorporation into a greenhouse IPM program is one that is pest specific and not harmful to biological control agents of that pest, or those of other pests in the system (Kaspi & Parrella, 2005). Although not harmless to parasitoids, the use of abamectin can be successfully integrated with augmentative releases of the parasitoid *Diglyphus isaea* (Walker) for management of *L. trifolii* (Kaspi & Parrella, 2005). They found that the residual period for abamectin was approximately 1 week. By releasing parasitoids after that time, the abamectin would no longer be toxic for the parasitoids. In this manner, an early season application of abamectin could sharply lower *L. trifolii* populations quickly, and released parasitoids could then provide longer term management of *L. trifolii*. *Diglyphus isaea* larvae paralyze their hosts, and consequently some *D. isaea* larvae would be protected from abamectin sprays because their hosts would no longer be feeding to ingest the toxin. As with the IPM programs for field grown vegetables discussed above, this integrated management program for greenhouse leafminers presents several advantages for growers. Because released parasitoids are self-perpetuating, a single release may substitute for several insecticide applications. Again, this integrated approach reduces the probability of resistance developing. Also, this approach could reduce inputs for growers without sacrificing crop yield and quality. This integrated management program for *L. trifolii* could be expanded into a more comprehensive program by determining how various insecticides and natural enemies for other pests interact with one another.

6. Conclusions

Growers around the world have experienced significant problems from *Liriomyza* leafminers. They continue to invest considerable resources in the management of these pest flies. Despite the long history of problems with leafminers, many of the lessons that have been learned in one area at one time have, unfortunately, had to be relearned elsewhere. Leafminers are classic secondary pests. If the parasitoid complex that attacks leafminers is conserved, economic damage from leafminers can be mitigated. Still, there are clearly circumstances where insecticides are needed to suppress leafminer populations below economically damaging levels. In particular, there may be cases where the lag in the increase in parasitoid populations may allow leafminer populations to exceed economic threshold levels. In such situations, growers should select insecticides that will minimally disrupt the parasitoid complex. First and foremost, though, it is imperative that researchers provide growers with realistic economic action thresholds for different cropping systems so that growers have a clear understanding of when their crop may be at risk. Indeed, insecticide treatments may not always be warranted for seemingly high populations of leafminers. Marketable yield for a crop like tomato may not be lowered until exceedingly high levels of leafmines are reached (Levins et al., 1975).

In a similar vein, when other pests reach economic threshold levels and require therapeutic insecticide treatments, growers are encouraged to consider the effect of those insecticide treatments on leafminer management. Proactive management decisions will reduce the likelihood of inducing severe outbreaks of leafminers. It is possible to produce a crop with few, if any insecticide treatments for leafminers, but this will best be realized if all growers in a community adopt similar IPM programs so that any one grower does not adversely affect neighboring growers. Continuing forward, the basic strategies for leafminer management are clear. However, the practical implementation of such strategies will remain a challenge. There is an ongoing need for development of selective, reduced risk insecticides to incorporate into leafminer management programs and to ensure that appropriate resistance management programs are developed. Further, there is a clear need for improved diagnostic methods and characterization of biological variation among biotypes and cryptic species of pest *Liriomyza*. Because other species share traits with the major pest species, it may be possible that new species of *Liriomyza* may emerge as global threats, as have *L. huidobrensis*, *L. sativae* and *L. trifolii*.

Because invasions are most likely to continue into the future, it will be critical to accurately identify new invasive species and populations, and to monitor changes in leafminer population dynamics following invasions. As these leafminers will continue to be important pests of high value crops, insecticides will continue to be an important component of leafminer management. Therefore, it is imperative to continue to refine the use of insecticides that target leafminers. Improving application timing and methods will help to conserve insecticide susceptibility and maintain efficacy by mitigating the evolution of resistance. Insecticide resistance management must remain as a critical component of IPM. Furthermore, improving strategies for the conservation and augmentation of leafminer parasitoids will help reduce the need for insecticide applications. Knowledge gaps in regard to the effects of insecticides on various leafminer parasitoids should continue to be addressed. Leafminer management will best be accomplished through research on, and implementation of, comprehensive IPM strategies.

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