Behavioral control of apple maggot fly (Rhagoletis pomonella) in Massachusetts commercial apple orchards.

BEHAVIORAL CONTROL OF APPLE MAGGOT FLY (*Rhagoletis pomonella*) IN MASSACHUSETTS COMMERCIAL APPLE ORCHARDS

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CHAPTER 1

MASS-TRAPPING TECHNIQUES FOR BEHAVIORAL CONTROL OF KEY ARTHROPOD PESTS

1.1 General Considerations

The intent of integrated pest management (IPM) is to look at the entire pest complex affecting a particular system(s) and use multiple, decision-based approaches to manage the whole pest system in an ecologically and economically sound manner (Prokopy and Kogan 2003). Foster and Harris (1997) define a pest as anything that threatens a resource valued by humans, including human health. This includes not only arthropods, but pathogens (fungi, viruses), vertebrates, and weeds. Historically, protection of resources through pest control was accomplished through chemical management using broad-spectrum pesticides. However, due to an increased awareness of risks associated with pesticide use, as well as the increasing occurrence of pest resistance to insecticides, it has become more common over the past few decades to decrease reliance on pesticides and increase the use of alternative management techniques. Currently, most IPM practitioners use information about pest ecology and behavior primarily to know when it is necessary to spray pesticides, and less so to find alternative management methods (Prokopy and Roitberg 2003). While this has drastically reduced pesticide use, it ignores the larger goal of IPM, which is to manage pests through integrated methods that take into account the entire pest complex. Such methods include behavioral, cultural, genetic, biological, and chemical approaches to control (Prokopy and Roitberg 2003).

Most forms of pest control can, in some way, effect a change in pest behavior (Gould 1991). Foster and Harris (1997) state that functionally, manipulation of a pest's behavior results from practices that either stimulate or inhibit a behavior and is dependent mainly on five key attributes: 1) accessibility: the stimulus must be suitable for presentation in a form that the insect can perceive, 2) definability and reproducibility: the more precisely that the stimulus can be defined, the more precisely it can be reproduced artificially, 3) controllability: controlling various parameters of a stimulus, especially intensity and longevity, will give greater control in behavioral manipulation, 4) specificity: the more specific a stimulus is to a particular behavior of a pest, the more likely it is to be perceived by the pest and therefore able to manipulate that behavior (a stimulus must have sufficient intensity and quality to be perceived by the insect above background level stimuli) and 5) practicability: stimuli used should be within practical limits; simple, economical, and specific to target. It may be that the stimuli used to manipulate pest behavior are natural, such as attractive trap crops to draw pests away from a valued crop (Hokanen 1991) or intercropping with an unattractive plant that may disrupt host finding behavior (Finch and Collier 2000). Foster and Harris (1997) note that artificial stimuli are generally more flexible and easier to manipulate in behavioral control than natural stimuli. Prokopy and Roitberg (2003) define artificial stimuli as either chemical or physical. Chemical stimuli include both olfactory cues that act over some distance and contact chemical stimuli, which are perceived upon arrival. Physical stimuli include visual, acoustic, or mechanical stimuli which are usually perceived from some distance away. While it is essential to consider the above five attributes when choosing a stimulus (either natural or artificial) for behavior-based manipulation, it is equally important to consider environmental factors which may influence the effectiveness of the stimuli.

More often than not, behavioral manipulation acts on external receptors, namely visual, olfactory, mechanical, or auditory receptors (Harris and Foster 1995). Chemical cues are frequently exploited in IPM practices, which is not surprising considering they are often very important to pest behavior, such as mate and host finding behavior (Cardé and Bell 1995). Chemical (or any) stimuli can be used in many ways to elicit a behavioral response from a pest. Chemical attractants can be used to prohibit pests from finding either a resource or potential mates. The most common way to disrupt finding behavior is pheromone inundation, which can be used to control certain (usually lepidopterous) pests. Pheromone cues essential in mate finding behavior can be masked by inundating an area with synthetic female odor, making it difficult for males to find potential mates. This can not only protect the resource from potential ovipositional damage, but also reduce pest population sizes below damaging levels (Cardé and Minks 1995, Fadamiro and Baker 2002).

1.2 Attract and Kill: Relevant Examples

Although chemical inundation can be a successful way to control certain pests via disruption of finding behavior, this thesis will focus on attract and kill, or mass trapping strategies using olfactory and/or visual cues. Mass-trapping techniques are meant to remove as much of the pest organism from the environment as possible, with the intent of providing protection of the resource (Foster and Harris 1997). Olfactory cues, such as pheromones or, more commonly, food lures, are often used in attract and kill strategies because, as mentioned above, they are integral to arthropod behavior. Visual stimuli, such as color and form of traps, are also important in behavioral manipulation methods by eliciting landings from responsive insects (Prokopy 1968, Phillips and Wyatt 1992). Alone or together, olfactory and visual cues are the subject of a number of studies using attract and kill (mass-trapping) strategies for behavioral management of arthropod pests. There have been many successful attempts to manage arthropod pests using this method. The following paragraphs will detail some of the more relevant studies involving visual and/or olfactory mass-trapping techniques and also examine some of the factors (especially environmental factors) that may influence the effectiveness of these techniques.

Mountain pine beetles (*Dendroctonus ponderosae*; Coleoptera: Scolytidae) are a major pest of lodgepole pine in the western United States. These beetles, in combination with a symbiotic fungus, kill host trees by damaging the phloem. Beetle populations can be contained by baiting trees in a grid-like fashion throughout the forest with a combination of female and male-produced aggregation pheromones (trans-verbanol and exo-brevicomin, respectively) and a host odor volatile, myrcene (Borden et al. 1983). Baited trees can be cut down and removed or treated with insecticide to kill the pine beetles (Borden 1989).

Environmental factors play a large role in the susceptibility of trees to mountain pine beetles. Mountain pine beetles require large pest densities to attack host trees; otherwise they are unable to overcome natural host defenses, such as resins (Raffa 2001). It has been shown that lower temperatures promote synchronized adult emergence. Therefore, if temperatures are high enough, adult emergence can be diffuse, which can reduce the likelihood of a pest outbreak (Bentz et al. 1991, Logan and Bentz 1999). Mountain pine beetle outbreaks have also been shown to decrease in trees that are highly thinned, mostly on the lower half of the tree. Thinned host trees are more vigorous, which may be one reason for the decreased pest outbreaks. Alternatively, a change in microclimate around the thinned trees may provide a less suitable environment for the beetles (Mithcell et al. 1983, Amman et al. 1988).

Another group of scolytid pests in the western U.S. is ambrosia beetles, in particular *Gnathotrichus* spp. and *Trypodendron lineatum*. These species are major pests of stored logs due to symbiotic fungi that they carry and introduce onto the logs. This fungus, which is the food source for the beetles, stains the logs, reducing their market value (Lindgren 1990). Kairomones (namely ethanol) and the aggregation pheromones sulcatol and lineatin released by logs serve as an attractant for invading beetles. Traps baited with these compounds provide effective control of these pests by capturing most alighting beetles, while others are drawn to nearby logs which can be processed before damage occurs (McLean and Borden 1977). Age and moisture content of logs affect their relative susceptibility to ambrosia beetles. Logs that are exposed to rain for a few months produce more ethanol and are therefore more susceptible than logs that are either freshly cut, protected from rain, or have branches still attached (Kelsey 1994, Kelsey and Joseph 1999). Trap densities can be modified to reflect these conditions in order to maintain trap effectiveness.

There are two worthy examples of successful mass-trapping programs for key dipteran pests, namely the tsetse fly in Africa and the olive fruit fly in Greece. These two pests have seen widespread implementation of the behavioral control programs discussed below.

The tsetse fly (*Glossina* spp., Diptera: Glossinidae) in Africa is by far one of the best examples of using visual plus olfactory cues to mass trap insects (male or female). Tsetse flies are major pests because they feed on the blood of native animals, livestock, and humans and pass on the microorganisms that give rise to sleeping sickness in humans and economic damage to livestock. Tsetse flies have a major economic impact in many parts of Africa.

Control methods for tsetse flies in Africa include a sterile male release program that has been very successful, virtually eliminating tsetse fly in some countries (Vreysen et al. 2000). There is also a mass-trapping program that has had a good amount of success using visual and olfactory lures. Tsetse flies respond to a combination of visual and chemical (host odor) cues (Colvin and

Gibson 1992). Combining visual and olfactory stimuli appears to increase the fly's propensity to find and land on target traps (Torr 1989). Vale et al. (1988) describe vertical visual targets used in Zimbabwe. Sheets of black cloth, 100 x 80 cm, bordered on either side by 100 x 70 cm sheets of black netting, are impregnated with the insecticide deltamethrin. These sheets were baited with synthetic attractive host odor consisting of octanol plus either acetone or butanone and deployed every 3.5 km^2 in infested habitats. These attracticidal traps resulted in a 99% reduction in tsetse populations over a 600 km^2 treated area during a 10-month study period.

In a detailed study, Vale (1988) illustrated the importance of understanding environmental conditions as related to behavioral control of tsetse flies. Vale found that the ability of tsetse flies to locate odor stimuli depended strongly on habitat structure. In the absence of natural hosts, tsetse flies tend to fly into gaps in vegetation to locate hosts. Traps placed within vegetation have little effect on capturing flies, whereas traps placed in openings in vegetation, especially if there is an open path downwind from the odor, are very successful in attracting and capturing flies.

Olive fruit fly (*Bactrocera oleae*, Diptera: Tephritidae) is a major pest of olives in the Mediterranean. Traditional control of the olive fly involved ground-applied bait sprays of protein and insecticide (Broumas et al. 2002). In the past two decades, there has been a very successful effort to behaviorally control olive fruit fly in Greece through the use of attracticidal traps (Haniotakis et al. 1986, Haniotakis et al. 1991). It is known that females of this species produce multiple mating pheromones to attract males. One form of one of these pheromones was found to also be produced by males and appears to elicit an aggregation response by females (Mazomenos and Haniotakis 1981, Haniotakis et al. 1986). A pesticide-treated wooden board trap was developed as a mass-trapping mechanism and was baited with a combination of female-produced sex pheromone, male-produced aggregation pheromone, a feeding stimulant, a food attractant, and glycerol (for moisture). The board traps are not only an effective control method compared to traditional bait sprays, but are also economically feasible, and have replaced bait sprays throughout Greece (Haniotakis et al. 1991, Broumas et al. 2002).

1.3 Attract and Kill: Apple Maggot Flies

The apple maggot fly, *Rhagoletis pomonella* (Walsh), has had a long history of successful behavioral control in some orchards in New England. Apple maggot fly (AMF) is a key pest of apple trees in eastern North America (Dean and Chapman 1973). Flies immigrate into commercial apple orchards from surrounding habitats, where large populations are maintained on wild unmanaged hosts (Prokopy et al. 1990, Bostanian et al. 1999, Prokopy et al. 2000, Bostanian and Racette 2001). Female AMF oviposit in apples and cause injury that reduces the value of the fruit. They locate host trees and apples within trees using a combination of host odor and visual stimuli (Aluja and Prokopy 1993, Prokopy et al. 1994). Female apple maggot flies can rapidly cause substantial damage to unmanaged fruit (Glass and Lienk 1971). It was discovered that AMF are attracted to red sphere traps that are slightly larger in size than apples (8 cm diameter) and placed in a visibly apparent position within the canopy of apple trees (Prokopy 1968). These traps are covered with a sticky substance (Tanglefoot) in order to capture alighting flies. AMF injury was successfully prevented by these traps when traps were placed in every tree in an orchard (Prokopy 1975). Reissig et al. (1982) later discovered an attractive host odor volatile, butyl hexanoate, which, when used by Prokopy et al. (1990) in combination with sticky sphere traps placed every 5 meters on perimeter-row trees, provided the same level of protection (<1% fruit injury) as non-baited spheres in every tree. Maintaining the current system of baited red spheres covered with sticky coating is labor intensive and costly. Spheres must be cleaned every 1-2 weeks, and the sticky coat must be reapplied at least twice during the season. Recent research is focusing on modifying the current design to provide a cost effective behavioral management system for growers in eastern North America. This can be done by providing a lower cost alternative to the current red sticky sphere and by maximizing sphere efficiency in attracting AMF so as to minimize the number of spheres needed for adequate control. The former is currently being developed in the form of a wooden or plastic sphere treated with pesticide, and supplied with a feeding stimulant (sucrose), which has so far proven to provide the same level of control as sticky spheres and grower sprays in commercial orchards (Prokopy et al. 2000). The latter is the focus of research detailed in the following chapters of this thesis.

It has been known for some time that there is a variety of environmental factors that influence the effectiveness of odor-baited red sphere traps in capturing AMF. Traps may perform differently in situations of higher or lower AMF populations. AMF populations in a given orchard can vary based on a number of factors. For instance, some apple cultivars are more susceptible to AMF injury than others. Flies tend to be more likely to infest redder, earlier-ripening, or softer-skinned cultivars (i.e. Gala, Akeene) and are less likely to infest greener, later maturing, or firmer cultivars (i.e. Golden Delicious, McIntosh) (Rull and Prokopy, unpublished data). Cultivars that are more susceptible to AMF may attract a larger number of flies into commercial orchards, therefore giving rise to higher AMF populations. Some data suggest that traps in Massachusetts orchards having relatively susceptible perimeter-row cultivars may capture more flies than traps in orchards with relatively tolerant perimeter-row cultivars (Prokopy et al. in press). Also, Bostanian and Racette (1999) and Bostanian et al. (2001) determined that perimeter traps in cultivars that were relatively susceptible to AMF captured significantly more flies than traps in relatively tolerant cultivars. They also showed that fruit of susceptible cultivars suffered much higher AMF damage than fruit of tolerant cultivars. Further, this information was then used to establish an effective attract and kill program in Quebec by spacing perimeter-row traps according to relative cultivar susceptibility to AMF, as well as considering potential entry points for AMF from nearby habitats, as discussed in greater detail below.

The habitat neighboring orchard blocks plays a key role in the size of immigrating AMF populations. As mentioned above, large populations of wild AMF are maintained on native hosts in New England. Neighboring habitats that are more likely to harbor AMF hosts (such as woods or hedgerows) would seemingly give rise to higher populations of AMF in nearby orchard blocks than habitats that may have fewer hosts (such as open fields). Indeed, results from some field studies indicate that traps in blocks adjacent to woods or hedgerows capture more flies than traps in blocks adjacent to open fields (Prokopy et al. in press).

Aside from the potential effect of AMF population size on trap effectiveness in preventing immigration of AMF into interiors of orchard blocks, there are also concerns with the placement of baited red sphere traps that greatly influence trap ability to intercept immigrating flies. Sphere position within the tree canopy has a major impact on AMF ability to readily perceive the trap. It is known that if fruit and foliage are cleared away at too great a distance from traps, flies that are moving about within the tree canopy may be less able to detect a trap (Roitberg et al. 1982, Roitberg and Prokopy 1984), and if fruit and foliage are not cleared away at a distance great enough from traps, traps may become obscured towards the end of the season as fruit grow and ripen (Reissig 1974, Rull and Prokopy 2001). Past studies have shown that traps are maximally conspicuous when placed 2-3 m off the ground, in the outer third of the canopy, with fruit and foliage cleared to a radius of 25-50 cm around the trap (Drummond et. al. 1984). However, these studies evaluated unbaited traps in apple trees, and did not include information on trap effectiveness at differing time intervals across the season (i.e. early, middle, and late season). Consideration of these factors may change optimal distances for clearing fruit and foliage around traps.

Finally, apple tree size may affect trap ability to intercept immigrating AMF. When perimeter-row traps are spaced 5 m apart, traps in small trees (M.9 rootstock) and medium size trees (M.26 rootstock) appear to be better at preventing AMF from entering the interior of orchard blocks than traps in large trees (M.7 rootstock) (Prokopy et al. 2001, Rull and Prokopy 2001).

D. Relevance of Existing Knowledge to Thesis Objectives

The objective of my thesis research, broadly, is to optimize the ability of red sphere traps to attract and capture apple maggot flies and to examine factors that may affect the efficacy of traps. This is done not only by evaluating potential improvements upon current odor and visual stimuli, but also by examining, in greater depth than heretofore, the potential influence of environmental factors on trap performance in orchard settings. The discovery of a new, more attractive odor lure (consisting of a blend of 5 apple odor volatiles (Zhang et al. 1999)) has allowed for the potential to increase the distance between sphere traps on perimeter rows of apple trees. Some data suggest that spheres placed at 10 m apart on perimeter-row trees (requiring only half as many spheres as placement at 5 m apart) and baited with the above 5-component blend lure may provide the same level of protection against AMF injury as grower sprays and blend-baited spheres placed at 5 m apart (Prokopy et al. in press). The second chapter of this thesis focuses on a two-year study that evaluates the effectiveness of this 5-component blend as compared to butyl hexanoate (a single component of the 5-component blend, evaluated here at two different release rates) for attracting AMF and preventing AMF from penetrating through the trapped perimeter rows and damaging fruit within orchard blocks (with all perimeter-row traps spaced 10 m apart). The second chapter also examines the impact of cultivar susceptibility to AMF on perimeter-row trap performance and possible differences in outcome due to nature of surrounding habitat (woods, hedgerow, or open field). The impact of odor-bait type, perimeter-row cultivar susceptibility to AMF and adjacent habitat composition were evaluated by counting wild flies captured by traps, counting lab-reared marked flies captured by traps (where flies were released in the habitat adjacent to perimeter-row trees), and by assessing percent of fruit injured by AMF.

While reducing sphere numbers obviously reduces cost, optimizing sphere position within trees will maximize visual apparency of spheres to AMF and ensure trap effectiveness across the entire growing season. As discussed above, there are many factors which influence trap conspicuousness to AMF. Some observational and experimental evidence suggests that perhaps the traditional optimal distance for clearing fruit and foliage may become less than optimal as the season progresses and ripening fruit increasingly competes visually with red sphere traps (Rull and Prokopy, in press). Also, past studies in this area have either involved unbaited red sphere traps or traps baited with butyl hexanoate. Perhaps use of the 5-component blend of attractive odor in association with a trap could affect criteria for optimal positioning of traps. The third chapter of this thesis re-evaluates traditional sphere positioning for mass trapping AMF. Experiments were conducted comparing distances from blend-baited traps to which fruit and foliage were cleared (both in a relatively AMF susceptible and a relatively AMF tolerant cultivar) and the effect of clearance distance as expressed during different parts of the AMF season. These studies also compared two different-sized spheres (the traditional 8 cm diameter sphere and a larger 12.5 cm diameter sphere) to determine whether distance at which fruit and foliage were cleared interacted with sphere size in affecting capture of AMF on spheres.

Hopefully, through careful examination of variation of chemical stimuli and evaluation of environmental factors affecting the efficacy of sphere traps, a framework will have been developed for ensuring maximum efficacy of such traps in preventing AMF from injuring fruit across the entire season, and doing so at minimal cost (no more than the cost of traditional sprays). The results of this research should help to promote optimal placement of pesticide-treated spheres in orchards, with the intent of implementing an attract-and-kill technique on a widespread commercial scale.

CHAPTER 2

INFLUENCE OF ODOR-BAIT, CULTIVAR TYPE, AND ADJACENT HABITAT ON BEHAVIORAL CONTROL OF APPLE MAGGOT FLIES (*RHAGOLETIS POMONELLA*) IN MASSACHUSETTS COMMERCIAL APPLE ORCHARDS.

2.1 Introduction

Behavioral control of key arthropod pests frequently utilizes the concept of mass-trapping, or trapping enough of the damaging stage of the pest to achieve successful management. This technique has often used a host mimic coupled with an attractive odor to attract and trap the target pest, many times with successful results (eg. McLean and Borden 1977, Borden et al. 1983, Vale et al. 1988). Among tephritid fly pests, this approach has been used successfully in controlling the olive fruit fly (*Bactrocera oleae* (Gmelin)), the Mediteranean fruit fly (*Ceratitis capitata* (Wiedemann)) and the apple maggot fly (*Rhagoletis pomonella* (Walsh)). Haniotakis et al. (1991) and Broumas et al. (2002) have had success using an odor-baited pesticide-treated board to mass-trap the monophagous olive fruit fly in Greece. Mass-trapping via perimeter traps, or traps surrounding the perimeter of an orchard block, has shown promise for controlling Mediterranean fruit flies, a polyphagous tephritid pest that frequently penetrates orchards from surrounding habitats (Cohen and Yuval 2000).

Behavioral control of apple maggot flies (AMF) in eastern North America relies upon an approach similar to that used against Mediterranean fruit flies: odor-baited red sphere traps placed on perimeter-row trees of apple orchard blocks. Such spheres intercept adult AMF immigrating into commercial orchards from unmanaged native hosts (Prokopy et al. 1990; 1996; 2000; Bostanian et al. 1999; Bostanian and Racette 2001).

Traditionally, red sphere traps have been baited with the attractive apple odor volatile butyl hexanoate (BH) as described by Fein et al. (1982). In Massachusetts, this bait has usually been coupled with traps spaced 5 m apart, a distance based on a limited number of field studies suggesting that front-row traps spaced 5 m apart are more effective at preventing AMF penetration into orchard blocks than are front-row traps spaced either 10, 20, or 40 m apart (Prokopy et al. 1990; Christie et al. 1991). More recently, a more attractive odor lure has been discovered: a five component blend of apple volatiles described by Zhang et al. (1999). Prokopy et al. (2003) determined that front-row traps baited with this blend and spaced 10 m apart were just as effective as blend-baited front-row traps spaced 5 m apart.

An important consideration when determining trap spacing on the perimeter row is the relative susceptibility of different apple cultivars to AMF. Experiments conducted in apple orchards in Quebec have suggested that relative cultivar susceptibility plays a key role in the efficacy of red sphere traps. Bostanian et al. (1999) and Bostanian and Racette (2001) showed that perimeter traps in cultivars that were relatively susceptible to AMF captured significantly more flies than traps in relatively tolerant cultivars. They also showed that fruit of susceptible cultivars suffered much higher AMF damage than fruit of tolerant cultivars. In Quebec, this information as well as adjacent habitat composition (potential entry points for AMF) have been used to determine how far apart to space perimeter-row traps for effective behavioral control of AMF. Similarly, in their 2000 study, Prokopy et al. (2003) evaluated the impact of apple cultivar susceptibility to AMF as well as adjacent habitat type on flies captured by traps. They showed that apple orchards that have perimeter rows comprised of trees that are relatively susceptible to AMF may be subject to more AMF pressure than those with relatively tolerant perimeter-row cultivars and that more AMF are captured in plots adjacent to woods or hedgerows than plots adjacent to open field.

In 2001, we evaluated the effectiveness of front-row traps baited with blend or butyl hexanoate at intercepting immigrating AMF and preventing them from penetrating into orchard blocks. Based on 2001 results, which indicated that blend and butyl hexanoate were similarly effective at preventing AMF from penetrating into orchard blocks, even though blend-baited front-row traps captured significantly more AMF than traps baited with BH, we hypothesized that both odor baits may have been stronger than necessary to attract immigrating flies and in fact may have drawn wild flies from a distance greater than normal, therby adding to AMF pressure on an orchard. Hence, in 2002, we evaluated a reduced release rate (25%) of the less attractive odor (BH) in an attempt to understand better the relationship between odor attractiveness and ability to prevent flies from entering orchard blocks. In both years, we assessed the effect of front-row cultivar composition and adjacent habitat type on the performance of baited red sphere traps. AMF penetration was measured by examining wild fly captures on traps as well as capture of flies that were marked and released in habitat adjacent to the front row of each block.

2.2 Materials and Methods

2.2.1 Orchard Block Design

Our experiments were conducted in 2001 and 2002 in 12 blocks in ten Massachusetts commercial apple orchards. Blocks were approximately 120 m in length along the front row and seven rows of trees deep (about 35 m). Front-row trees in six of the blocks were comprised of cultivars that were relatively attractive to AMF (Gala, Jonagold, and Fuji), whereas the other six blocks had front row trees that were relatively tolerant of AMF (McIntosh, Empire) (Rull and Prokopy, unpublished data). Four blocks were bordered by woods, four by hedgerow, and four by open field. Adjacent habitat began 8-10 m from the front row of apple trees. There were four blocks each of small, medium, and large trees (M.9, M.26, and M.7 rootstock, respectively). Unfortunately, due to a limited amount of suitable available blocks, a completely balanced design was not possible.

Each block was divided into three plots: two baited-sphere plots and a grower sprayed plot (Fig 1). Baited plots received spheres baited with either 4 g of a five-componant blend of apple odor volatiles in a polyethylene vial (as described by Zhang et. al. (1999)) or 4 g of the apple odor volatile BH, also in a polyethylene vial (Fein et. al. 1982, Averill et al. 1988). In 2001, BH was deployed in its full concentration (100% Release Rate: 8 μg/day), whereas in 2002 BH was deployed at one-quarter strength (25% BH in 75% mineral oil- Release Rate: 2 μg/day). Sticky sphere traps consisted of 8 cm wooden spheres coated with Tangletrap (Great Lakes IPM, Vestaburg, MI). Baited plots had front row trees with sticky red sphere traps spaced 10 m apart baited with blend or one of the concentrations of BH. The remainder of each baited plot (two lateral rows and the back row) was surrounded by spheres spaced 5 m apart and baited with full-strength BH. This was necessary to provide protection against AMF entering from other parts of the orchard. Traps were deployed during the first week of July in both 2001 and 2002. Each baited plot was about 45 m in length along the front row and received no insecticide from mid-June through harvest. The third plot contained no baited spheres and was sprayed two or three times with an organophosphate insecticide to control AMF. This plot was about 30 m in length along the front row and was always on one end of the block to facilitate ease of grower spraying. Each of the three plots contained unbaited monitoring spheres distributed on the third and fourth rows. There were six monitoring spheres for each baited-sphere plot and four for each grower-sprayed plot. Such spheres were intended to measure the degree of AMF penetration into the interior of plots.

Although it would have been ideal to have included a fourth plot that contained no perimeter traps and received no sprays against AMF, this was not done because AMF are capable of quickly colonizing and damaging unmanaged plots (Glass and Lienk 1971). Because all blocks were in commercial orchards, growers would have endured too much risk if no measures were taken to control AMF.

Each year, traps were inspected once every two weeks beginning in early July and continuing through the end of September, for a total of six sample periods. At each sample period, wild flies were counted and traps were cleaned of all insects and debris. If necessary, Tangletrap was reapplied. Each year, percentage of fruit injury was measured in sample periods two through five. For each plot (Blend, BH, and grower sprayed), on row 1 (front row), and rows 3, 5, and 7 (back row), 40 fruit per row were examined randomly for AMF oviposition stings.

2.2.2 Marked-Released AMF

`AMF pupae were collected from fallen, infested apples in the fall prior to the year that they were to be released. They were stored through winter in a cold room at 3° C and were removed in late spring and kept at 25° C for about 30 days until adult ecolsion. Adults were placed in 30x30x30 Plexiglas cages with protein, sugar and water for 14-21 days, at which point flies were sexually mature.

Flies were removed individually from cages, placed under a piece of mesh and then marked with a tiny dot of Tester's (Tester Co., Rockford, IL) oil paint on their pronotum the day before they were released. Forty flies (20 males and 20 females) were released in front of the midpoint of each plot, 10 m into the adjacent habitat. Each set of 40 flies was marked similarly (i.e. blue-marked flies released in front of the blend plot, red-marked in front of the BH plot, and white-marked in front of the grower-sprayed plot). Each set was released from a 6x6x12 cm transparent plastic box containing protein, sugar and water. Each box was mounted on a wooden pole and was 20 cm above ground. All release boxes were shaded with artificially placed foliage to provide protection from the sun. Flies were released between 0900 and 1100 h, at which point the plastic film (Saran Wrap) covering an opening in the release box was removed and flies were allowed to leave the box. Within 24 h, an average of 95% of flies had departed the release boxes. AMF remaining in boxes after 24 h were deducted from the 40 that were intended for release.

All traps were inspected for marked AMF 5 days after release, and the percentage of released flies recovered in each plot was recorded. Only the released AMF captured in the plot directly opposite of their release site were included in the data. Releases occurred between mid July and early September. One release was made per plot.

2.2.3 Statistical Analysis

All data on captures of wild and marked-released AMF on baited front-row traps and unbaited interior monitoring traps and all data on percent fruit injury were submitted to ANOVA and least significant difference tests ($p \leq 0.05$).

2.3 Results

2.3.1 All Cultivars and Sample Periods

Across all sample periods, regardless of front-row cultivar type, the pattern of front-row trap captures of wild AMF each year was remarkably consistent among treatments, with each concentration of BH performing similarly in relation to the 5-componant blend. The overall ratio of wild flies captured on blend-baited front-row traps to wild flies captured on BH-baited front-row traps was 1.62:1 in 2001 (blend:100% BH) and 1.67:1 in 2002 (blend:25% BH). For each year, across all sample periods and regardless of cultivar type, blend-baited front-row traps captured significantly more wild AMF than front-row traps baited with either concentration of BH (Fig. 2). However, for unbaited interior monitoring traps, there were no significant differences in wild fly captures among any of the bait treatments or between any bait treatments and the grower-sprayed control (Fig 2).

Each year, across all sample periods and regardless of cultivar type, there were no significant differences among odor treatments in the percentages of marked-released AMF captured by front-row traps (Fig 2). In 2001, there were no significant differences among treatments in the percentage of marked-released flies captured by interior monitoring traps. In 2002, monitoring traps in 25% BH-baited plots captured significantly more marked-released flies than monitoring traps in sprayed plots (which captured no marked flies), but did not capture a significantly different amount of marked flies than monitoring traps in blend plots (Fig 2).

Each year, fruit injury was low in all plots, with no significant differences among treatments. In 2001, fruit injury was 0.21% in each type of baited plot and 0.08% in grower sprayed plots; in 2002, fruit injury was 0.24% in blend-baited plots, 0.23% in BH-baited plots and 0.21% in grower sprayed plots.

2.3.2 Susceptible Cultivars

For front-row cultivars that were relatively susceptible to AMF, in both 2001 and 2002, blend-baited front row traps captured numerically but not significantly more wild AMF than front-row traps baited with either concentration of BH (Fig. 3). In 2001, on interior monitoring traps in susceptible-cultivar blocks, significantly more wild flies were captured in 100% BH plots than in grower-control plots. In 2002, there were no significant differences among treatments in the number of wild flies captured on interior monitoring spheres. In 2001, there were no significant differences among treatments in percentages of marked-released flies recovered on front-row traps or in percentages of marked-released flies recovered on interior monitoring traps. In 2002, again there were no significant differences among treatments in the percentage of marked flies recovered on front-row traps, but significantly more AMF were captured on interior monitoring spheres in BH plots than on interior monitoring spheres in grower sprayed plots. As in 2001, the percentage of marked-released flies recovered on monitoring spheres in blend plots in 2002 was not significantly different from that in grower-control plots or BH plots.

2.3.3 Tolerant Cultivars

In blocks having front-row cultivars that were relatively tolerant of AMF, for each year, significantly more wild AMF were captured on blend-baited front-row traps than BH-baited front-row traps. For unbaited interior monitoring spheres, there were never any significant differences in wild fly captures among odor-baited treatments and the grower-control. For each year, there were no significant differences among treatments in marked-released fly captures on front-row traps, or interior monitoring traps. In both years, however, numerically more flies were recovered on front-row traps baited with blend, with this trend being most obvious in 2002, when blend was evaluated against the 25% concentration of BH (Fig 3).

2.3.4 Seasonal Trends

When wild fly trap capture data were evaluated for each sample period (six periods over the course of each year), trends remained similar across the season. For each year and each sample period, blend-baited front-row traps always captured numerically more AMF than BH-baited front-row traps. Differences between treatments, however, were never significant, with the exception of sample period 4 in 2002. Captures on unbaited interior monitoring spheres were always similar among the bait treatments and the grower control (Fig 4).

2.3.5 Adjacent Habitat

Each year, front-row traps adjacent to hedgerow captured numerically more wild AMF than front-row traps adjacent to woods, which in turn captured numerically more AMF than front-row traps adjacent to open field (Fig 5). However, differences were not significant except in 2001, when traps adjacent to hedgerow captured significantly more wild AMF than traps adjacent to open field. The pattern of capture of marked-released AMF differed from that of wild AMF, with captures by front-row traps adjacent to open field equaling or exceeding captures by traps adjacent to hedgerow or woods.

2.4 Discussion

Overall, results were similar for both years, with each release rate of BH performing similarly in relation to blend in terms of front-row trap captures. Over all sample periods for each year, and regardless of cultivar type, blend-baited front-row traps always captured significantly more wild AMF than front-row traps baited with either concentration of BH. However, these findings were not supported by marked-released fly data. For each year, blend-baited front-row traps never captured a significantly different number of marked-released AMF than BH-baited front-row traps. This could have been due to the fact that marked flies were released only 18-20 meters from front-row traps. Possibly they flew to the nearest trap (the central front-row trap). This was probably not the case, however, because captures of marked-released AMF on the front row tended to be spread out across all front-row traps in a plot. Alternatively, we propose that at close range (such as 18-20 m), both odors are equally attractive to AMF but that at a greater distance, blend odor bait is more likely than BH to draw AMF toward traps. Future experiments wherein marked flies are released at successively greater distances from front row traps would help to resolve this question.

Unbaited monitoring spheres on interior rows of plots and degree of fruit injury were our principle means of assessing the effectiveness of front-row baited traps in preventing AMF from penetrating into the interior of orchard blocks. Each year, there were no significant differences in the percentage of fruit injured by AMF among plot treatments. For the most part, there were no significant differences among plot treatments in AMF captures on interior monitoring traps. This indicates that for each year, regardless of cultivar type, the three plot treatment types (blend-baited, BH-baited, and grower sprayed) were generally equally effective at preventing AMF from entering plots. There were exceptions to this generality, however. When perimeter-row trees were comprised of relatively susceptible cultivars, monitoring spheres in BH plots captured significantly more wild AMF in 2001 and significantly more marked-released AMF in 2002 than did monitoring spheres in sprayed plots. Overall, our findings lead us to conclude that because blend-baited traps were never less effective than BH-baited traps in preventing AMF from penetrating orchard blocks, and because blend-baited traps were sometimes more effective than BH-baited traps in preventing AMF penetration of plots comprised of relatively susceptible-cultivar front rows, we would recommend that growers use blend bait rather than BH to attract AMF to traps for AMF control.

Similar to results of Prokopy et al. (2003) for the same orchard blocks, front row traps adjacent to woods or hedgerow captured numerically more wild AMF than front row traps adjacent to open field. These results were not surprising because native hosts that harbor the majority of wild AMF would be found primarily in the woods and hedgerow (Bostanian et al. 1999), and because AMF behave as though they could move much greater distances through patches of trees or shrubs than through open space (Green et al. 1994). In 2001, the percentage of marked-released AMF recovered on front-row traps adjacent to open field equaled that of traps adjacent to woods or hedgerow, and in 2002, significantly more marked-released AMF were captured on front-row traps in blocks adjacent to open field than on front-row traps in blocks adjacent to woods. Perhaps odor-baited traps were more conspicuous to AMF released in open fields, where there was no foliage (above grass height) to interfere with odor plumes from baited traps. Marked flies released in open fields were released much closer to front-row traps (18-20 m) than the distance at which wild flies would normally initiate movement towards orchards bordered by open field.

This two year study evaluated factors that may influence odor-baited trap effectiveness in controlling AMF in commercial orchard settings, with the intent of future substitution of non-sticky, pesticide coated sphere traps for sticky sphere traps to achieve widespread behavioral control (Prokopy et al. 2000). Although the results are not entirely conclusive, we feel confident in recommending the 5-component blend as the most useful lure for attracting wild AMF to odor-baited perimeter-row traps. We have determined that traps baited with this blend provide protection against AMF equivalent to that of grower sprays, based on low fruit injury (0.21-0.24%) and similar fly captures on monitoring spheres placed at the interior of plots. As demonstrated by Bostanian et al. (1999), Bostanian and Racette (2001), and as corroborated by Prokopy et al. (2003) as well as our findings here, odor-baited sphere traps in perimeter-row trees that are relatively susceptible to AMF capture a greater number of AMF than traps in relatively tolerant perimeter-row cultivars. These same studies indicate that the habitat adjacent to orchards blocks dictates, to some degree, the degree of threat posed by AMF to a given orchard block. Findings by Prokopy et al. (2001) and Rull and Prokopy (2001) indicate that perimeter-row traps in small and medium sized apple trees (M.9 and M.26 rootstock, respectively) appear to be better at preventing AMF from entering the interior of orchard blocks than perimeter-row traps in large apple trees (M.7 rootstock). Tree size, as well as cultivar susceptibility and habitat adjacent to orchard blocks are all important factors influencing the efficacy of odor-baited sphere traps because they potentially create situations of high or low AMF populations in orchard blocks. Future work will consider these influences on local AMF populations with respect to perimeter-row trap spacing. Results could modify trap spacing to accommodate these factors.

2.5 Description of Figures

Fig. 2.1. Schematic illustration of layout of test plots. X= trees without traps; ● = trees with an odor-baited sticky red sphere trap; ○ = interior trees with an unbaited sticky red sphere monitoring trap. There were five spheres spaced 10 m apart per front row in plots A and B (baited plots). Lateral and back rows of plots A and B were surrounded by sticky red sphere traps spaced 5 m apart and baited with full strength BH. Plot C had no baited traps and was sprayed by the grower with organophosphate insecticide. Plots A and B were randomly assigned in each orchard block.

Fig. 2.2. Across all 12 apple orchard blocks and all sample periods, for both 2001 and 2002, mean number (+/- SEM) of wild AMF (a) or mean percentage (+/- SEM) of marked-released AMF (b) captured by blend or BH-baited traps on front-row trees and by unbaited monitoring spheres placed within the interior of baited plots and the grower sprayed plots. For each fly type and treatment type, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 2.3. Across all sample periods, mean number (+/- SEM) of wild AMF (a, c) or mean percentage (+/- SEM) of marked-released AMF (b, d) captured by baited front-row spheres or unbaited interior monitoring spheres when orchards were segregated according to relative susceptibility of front-row cultivar to AMF (six blocks with susceptible front-row cultivars and six blocks with tolerant front-row cultivars). For each fly type and treatment type, mean values superscribed by

the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 2.4. Across all 12 orchard blocks, mean number (+/- SEM) of wild AMF captured by spheres when captures were segregated according to the six 2-week sample periods from mid-July (sample period 1) through the end of September (sample period 6). For each fly type and treatment type, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 2.5. Across all front-row traps in all plots and across all sample periods, mean number (+/- SEM) of wild AMF (a) or mean percentage of marked-released AMF (b) captured when orchard blocks were adjacent to woods, hedgerow, or open field. For each fly type, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

2.6 Figures

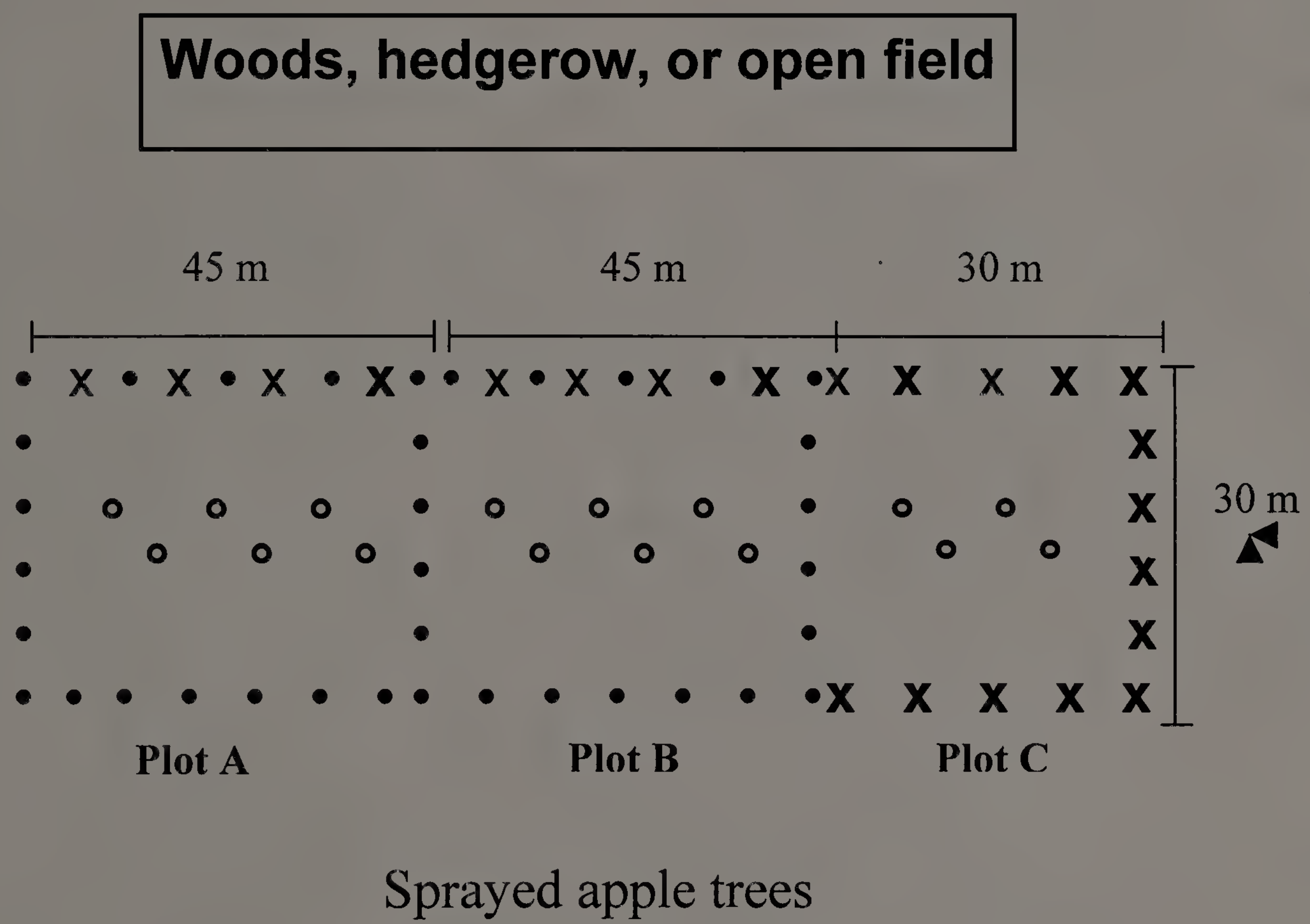


Fig. 2.1. Schematic of Orchard Blocks

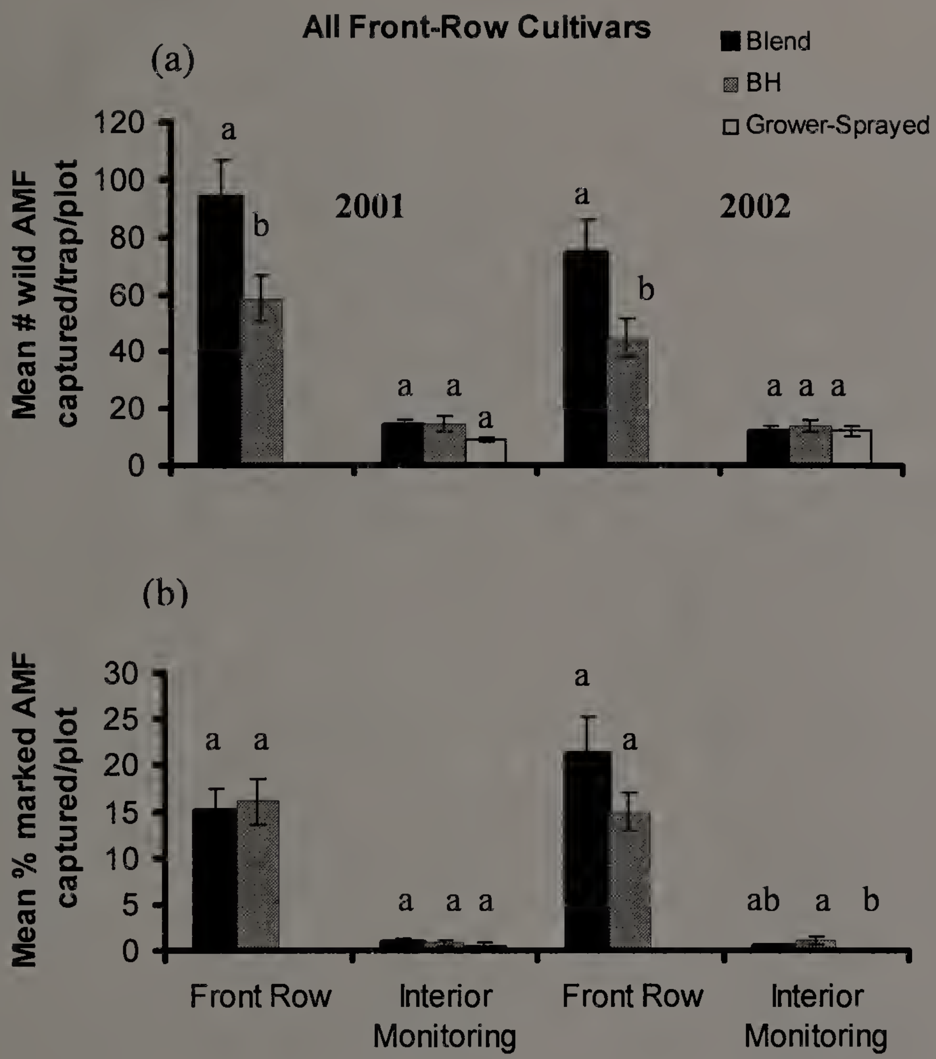


Fig. 2.2. AMF Captures foe All Cultivars

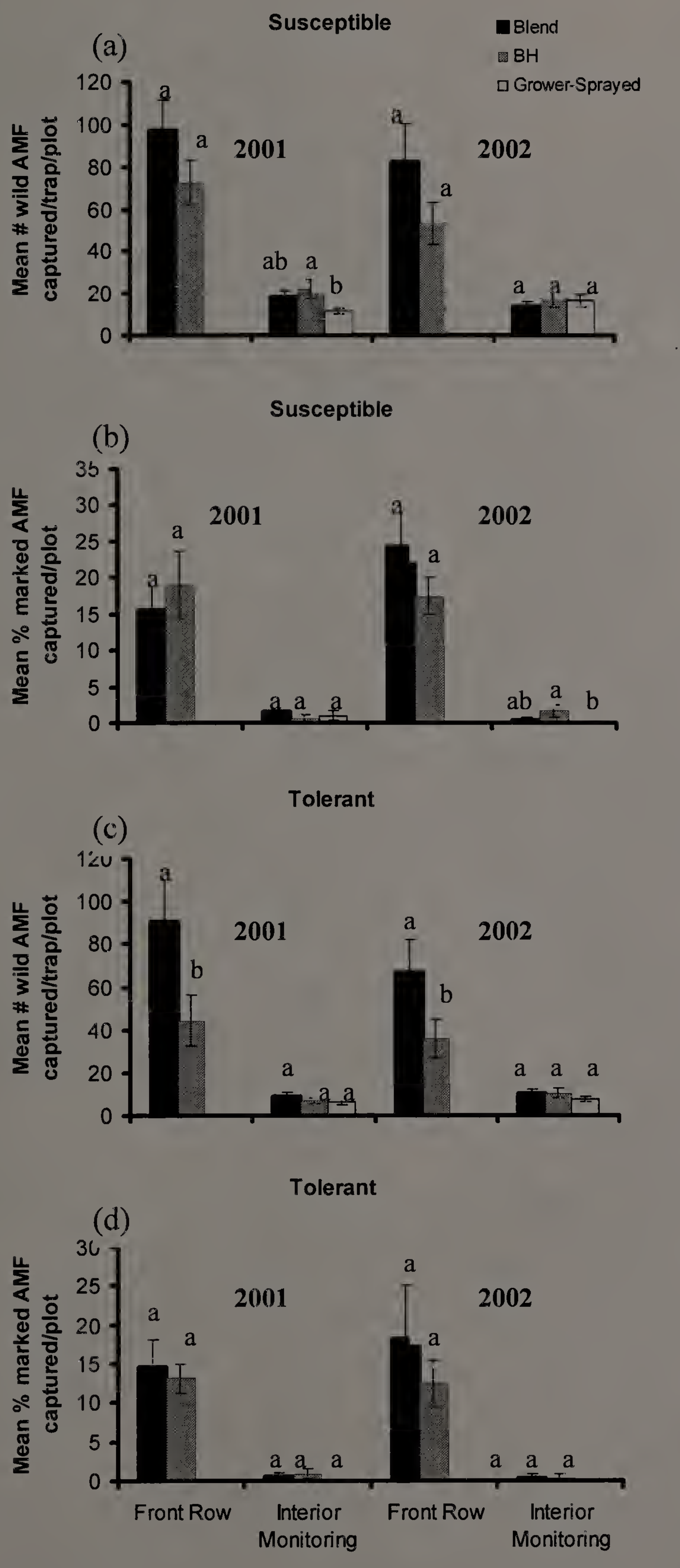


Fig. 2.3. AMF Captures for Susceptible and Tolerant Cultivars

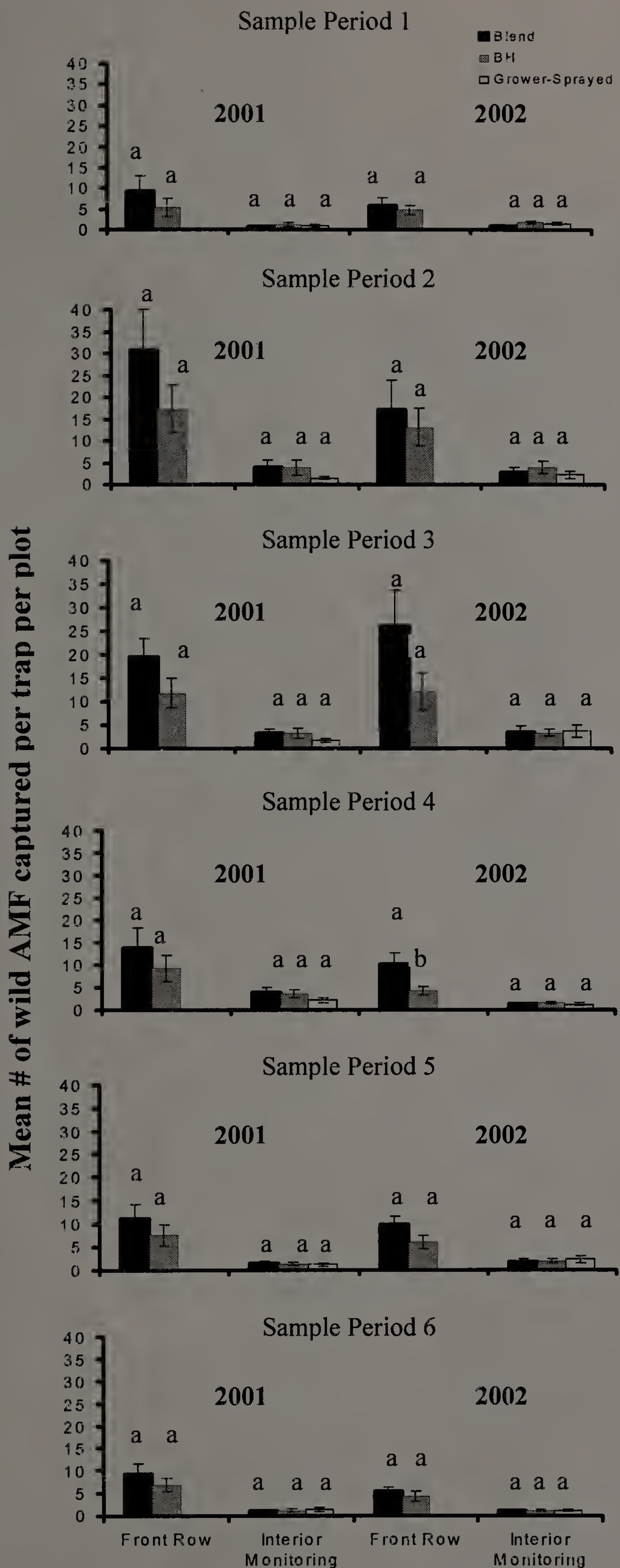
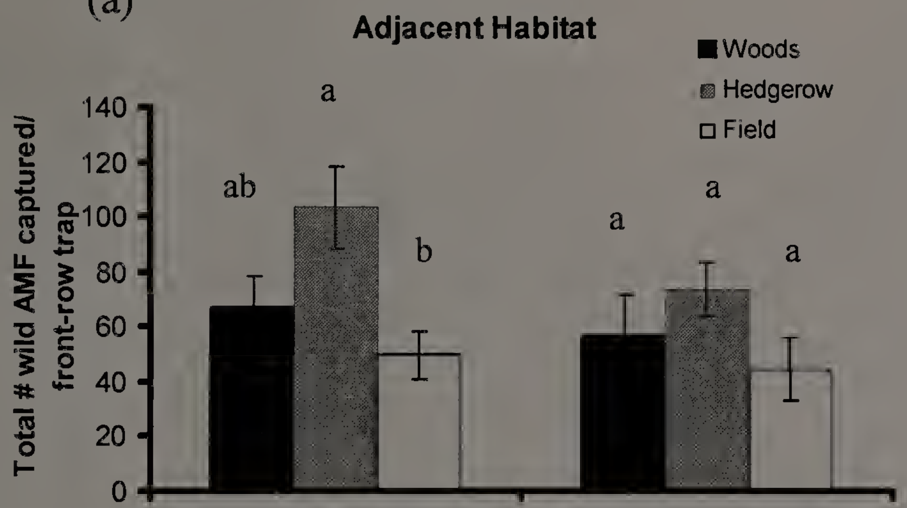


Fig. 2.4. AMF Captures by Sample Period

(a)



(b)

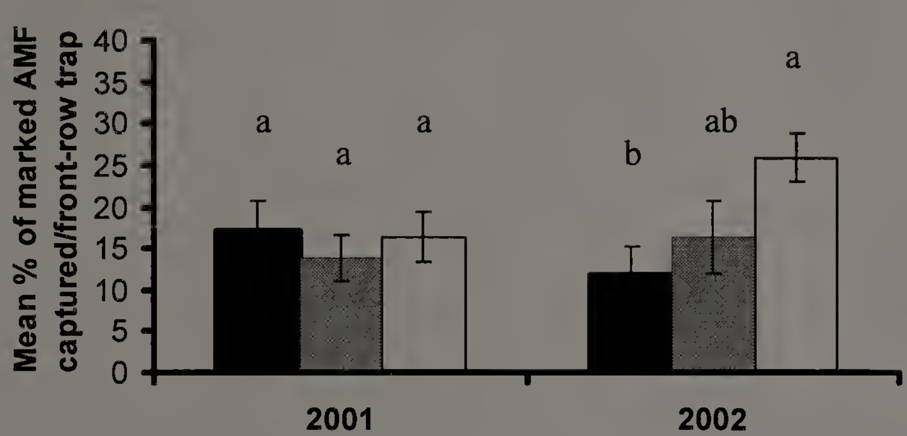


Fig. 2.5. AMF Captures by Adjacent Habitat

CHAPTER 3

BEHAVIORAL CONTROL OF APPLE MAGGOT FLY, *RHAGOLETIS POMONELLA* (WALSH): A RECONSIDERATION OF WITHIN-TREE SPHERE POSITIONING

3.1 Introduction

Apple maggot flies, *Rhagoletis pomonella* (Walsh), are a key pest of apples in eastern North America (Dean and Chapman 1973). Apple maggot flies (AMF) immigrate into orchard blocks from surrounding habitats, where large populations are maintained on native hosts (Bostanian et al. 1993, Prokopy et al. 1990, 2000). Behavioral control of AMF has relied on spherical red sticky traps that are baited with a synthetic attractive apple odor volatile and placed around the perimeter of orchard blocks to intercept immigrating flies (Prokopy and Mason 1996, Prokopy et al. 1996, 2000, Bostanian et al. 1999, Bostanian and Racette 2001).

A key consideration when using perimeter traps as an attract-and-kill strategy for AMF is visual conspicuousness of red sphere traps to apple maggot flies. In the past, Drummond et al. (1984) recommended that when sphere traps are placed in the tree canopy, fruit and foliage should be removed to create an open space of 25-50 cm radius around the trap. However, Roitberg (1982) and Prokopy and Roitberg (1984) suggested that while pruning fruit and foliage away may increase visual apparency of traps to AMF, there are tradeoffs involved, and this amount of pruning may be more than what is optimal. Under increasing amounts of open space around sphere traps, AMF may be decreasingly likely to detect spheres as they move within tree canopies, hopping from fruit to fruit, as is typical of AMF fruit-foraging behavior. In addition, some observational and experimental evidence suggests that as fruit grow and ripen during the season, what was an optimal trap position at the beginning of the season may become less so towards the end of the season (Reissig, 1974, Prokopy et al. 1995, Rull and Prokopy 2003, in press).

The experiments conducted by Drummond et al. (1984) were done with unbaited traps and did not take into account seasonality (i.e. early, mid, or late season). Rull and Prokopy (in press) tried to clear up points of uncertainty by examining fly captures on baited traps during the early, middle, and late part of the season for traps baited with a highly attractive odor blend and placed in different positions in apple trees bearing either red or yellowish fruit (Akeene and Golden Delicious, respectively). Traps were placed in a traditional optimal position (fruit and foliage cleared to 15 cm in a radius around the trap), a revised optimal position (foliage cleared to 15 cm and fruit cleared to 30 cm), and with artificial visual competition (3 plastic non-sticky red spheres placed 15 cm from the sticky trap). They concluded that addition of plastic red spheres did reduce trap efficacy (measured by AMF captures), that there was no reason not to thin fruit to a distance of 30 cm away from the trap (in both Akeene and Golden Delicious trees), and that this may in fact increase trap captures, especially towards the end of the season.

We desired to further examine some questions about trap position that remained unanswered from the Rull and Prokopy (in press) experiments. By considering a broader range of distances, we studied the optimal distance to clear fruit and foliage away from baited traps in order to maintain maximal efficacy across the entire growing season. We also aimed to determine if addition of a strong odor lure combined with greater open space around traps would alter the optimal size (8 cm) of sphere traps attractive to AMF, as determined by Prokopy (1977). Finally, we wanted to determine whether a larger trap coupled with an attractive odor lure would help overcome constraints associated with traps in sub-optimal positions.

3.2 Materials and Methods

3.2.1 Orchard Characteristics

All experiments were conducted in a city-owned apple orchard in Leominster, MA during the summer of 2002. For the Radius of Open Space Around Traps experiment, traps were placed in both Jersey Mac and Golden Delicious trees. Jersey Mac trees were of a medium size (M.26 rootstock) and contained a small to medium load of fruit, which turned red as it ripened. Jersey Mac trees are earlier ripening, and relatively susceptible to AMF ovipositional stings. Golden Delicious trees were larger in size (M.7 rootstock) and contained a large load of fruit which turned a yellowish color as it ripened. Golden Delicious trees ripen later in the season, and are relatively tolerant to AMF stings. This study was conducted in an otherwise managed apple orchard where treatment trees remained unsprayed with insecticide from early June until the end of the season.

3.2.2 Radius of Open Space Around Traps

This study evaluated the effect of varying amounts of cleared space around 8 cm diameter red sphere traps placed in Jersey Mac and Golden Delicious trees. All sphere traps were coated with a sticky substance (Tangletrap, Tanglefoot Co.; Grand Rapids, MI) and all received a 500 ml polyethylene vial containing an attractive apple odor blend (described by Zhang et al. 1999) placed approximately 15 cm away from the trap in each treatment tree. Fruit and foliage were cleared to three distances (in a radius around traps) in Jersey Mac trees (0, 25, and 50 cm) and 5 distances in Golden Delicious trees (0, 25, 50, 75, and 100 cm). For the 0 cm treatment, fruit and foliage were cleared away just enough to prevent them from touching the trap (approximately 2-3 cm). There were 6 replicates of each treatment in both Jersey Mac and Golden Delicious trees. Traps were hung in the tree 2-3 m above ground and about 1/3 of the way into the canopy. Each tree contained one sphere trap. There were more treatments in Golden Delicious trees because they were larger and allowed us to clear the fruit and foliage up to a distance of 100 cm from the trap. Traps were checked once a week, at which time wild flies were counted and traps were cleared of insects and debris. Also, traps were inspected each week to ensure that they were still in the proper position, and if necessary, fruit and foliage was pared back to the proper distance.

3.2.3 Size of Sphere

For this set of experiments, only Jersey Mac trees were used. See above for tree and spray details. There were two trap types: the traditional 8 cm diameter wooden sphere, and a larger 12.5 cm plastic sphere (Afloral.com, Celoron, NY). For each trap size, traps were placed in one of two places in the canopy (outer third or inner third-- approximately 2 m above ground), and fruit and foliage were cleared to two distances (25 cm or 50 cm), resulting in four conditions.

3.2.4 Sample Dates and Statistical Analysis

Sample dates were as follows: July 18, 25 and August 1, 2002= early season for Golden Delicious trees and mid season for Jersey Mac trees; August 8 and 15, 2002= mid season for Golden Delicious trees and late season for Jersey Macs; August 22, September 3, 9, and 20, 2002= late season for Golden Delicious and post-harvest for Jersey Macs. Unless otherwise stated, analyses were performed using ANOVA and least significant difference tests.

3.3 Results

3.3.1 Fruit and Foliar Clearing Distance Experiments

Across the entire season, in relatively susceptible Jersey Mac trees, there were no significant differences in AMF captures due to fruit and foliage clearing distance. This was also true when data were considered separately for the mid, late, and post-harvest part of the season (Fig. 1). Traps in the 0 distance category consistently caught only 47-48% as many AMF as traps in 25 or 50 distance categories.

Over the entire season, in relatively tolerant Golden Delicious trees, there were significant differences among treatments in AMF captures. Traps with fruit and foliage cleared to 25 or 50 cm captured significantly more AMF than traps with fruit and foliage cleared to 0 or 100 cm. Trap captures when fruit and foliage were cleared to 75 cm were not significantly different from either group (Fig. 2).

In Golden Delicious trees, in the early part of the season, there were no significant differences in AMF captures among treatments. In the middle part of the season, traps with fruit and foliage cleared to 25 or 50 cm captured significantly more flies than traps with fruit and foliage cleared to 0, 75, or 100 cm. Traps with fruit and foliage cleared to 75 cm captured significantly more AMF than traps with fruit and foliage cleared to 0 cm. Traps with fruit and foliage cleared to 100 cm did not capture a significantly different number of AMF than traps with fruit and foliage cleared to 0 or 75 cm (Fig 2). In the late part of the season, traps with fruit and foliage cleared to 25 or 50 cm captured significantly more AMF than traps with fruit and foliage cleared to 0 or 100 cm. Traps in the 25 cm treatment captured significantly more AMF than traps in the 75 cm treatment. Traps with fruit and foliage cleared to 50 cm did not capture significantly more AMF than traps with fruit and foliage cleared to 75 cm, which in turn, did not capture significantly more AMF than traps with fruit and foliage cleared to 100 cm (Fig 2).

3.3.2 Sphere Size Experiment

Across the entire season, 8 cm traps in the outer 1/3 of the tree canopy with fruit and foliage cleared to 50 cm (termed 50 cm out treatment) captured significantly more AMF than traps in the inner 1/3 of the tree canopy with fruit and foliage cleared to 25 or 50 cm (termed 25 cm in and 50 cm in treatments, respectively). Traps in the outer third of the canopy with fruit and foliage cleared to 25 cm (termed 25 cm out treatment) did not capture a significantly different amount of AMF compared with any other treatment (Fig. 3).

In the mid part of the season, for 8 cm traps, there were no significant differences in AMF captures among treatments. In the late part of the season, 8 cm traps in the 50 cm out treatment captured significantly more AMF than any other treatment. After harvest, 8 cm traps in the outer third of the canopy with fruit and foliage cleared to 50 cm captured significantly more AMF than 8 cm traps in the inner third of the canopy with fruit and foliage cleared to a 25 or 50 cm radius (Fig 3).

Across the entire season, 12.5 cm diameter traps in the outer third of the canopy, with fruit and foliage cleared to 50 cm, captured significantly more AMF than traps in the inner 1/3 of the canopy with fruit and foliage cleared to 25 cm. Fly captures on 12.5 cm traps in the 25 cm out treatment and traps in the 50 cm in treatment were not significantly different from each other or any other 12.5 cm sphere treatment. Among fly captures considered separately for the mid, late, or post-harvest part of the season, there were never any significant differences among 12.5 cm trap treatments (Fig 4).

Across the entire season, for each treatment type, t-tests show that 8 cm diameter traps captured significantly more AMF than counterpart 12.5 cm diameter traps (Table 1). Differences were not significant in the mid part of the season, but were significant for late season and post-harvest AMF captures, with the exception of the 50 cm in treatment in the late part of the season (Table 1).

3.4 Discussion

We expected to find that traps in relatively susceptible Jersey Mac trees with fruit and foliage cleared to 25 or 50 cm would capture significantly more AMF than traps with fruit and foliage not cleared away (0 cm treatment). Even though differences were not significant, traps with fruit and foliage cleared to 25 or 50 cm did indeed capture twice as many AMF than traps in the 0 cm treatment during mid and late season. Our findings, in Jersey Mac trees, though not showing significant differences, are nonetheless in general agreement with earlier evidence presented by Drummond et al. (1984) showing that unbaited traps were most effective when fruit and foliage were cleared to 25 or 50 cm, as opposed to 0 or 100 cm.

We did find significant differences among treatments in Golden Delicious trees. As expected, in early season there were no significant differences among treatments when fruit were small, but towards the middle of the season, as fruit grew, traps in trees with fruit and foliage cleared to 25 or 50 cm captured significantly more AMF than any other treatment. Toward the end of the season as fruit grew even larger, traps in trees with fruit and foliage cleared to 25 cm appeared to capture the most AMF, although not statistically more AMF than traps with fruit and foliage cleared to 50 cm.

Although Drummond et al (1984) found that spheres with fruit and foliage cleared to 25 or 50 cm were better at capturing AMF than spheres with fruit and foliage cleared to 0 or 100 cm, generally in orchard practice, fruit and foliage are cleared to a distance of 15-25 cm around a sphere trap. Doing so is based in part on evidence from field-case studies suggesting that AMF prefer trees with a heavy fruit load and that when fruit are numerous, AMF may prefer to make short flights to nearby fruit rather than larger flights to more distant fruit (or sphere traps) further away than 25 cm (Roitberg et al. 1982, Roitberg and Prokopy 1984). AMF detect fruit-mimicking spheres (as well as real fruit) based on spherical shape and contrast against background. Spheres are most conspicuous to AMF when set against a light background (Owens and Prokopy 1984). This would suggest that spheres surrounded closely by fruit and foliage ought to be less conspicuous and hence less detectable by AMF. Therefore as fruit grow and branches become heavy with developing fruit, a 15 cm radius may not be sufficient to prevent hiding of spheres, making a larger radius more ideal.

Results from the sphere size experiment confirm that more space around traps may be ideal. Traps of 8 cm diameter in the outer third of the canopy always captured numerically more AMF than 8 cm traps in the inner third of the canopy; however, this difference was significant only for the 50 cm out treatment. Overall, 8 cm spheres in the outer third of the canopy with fruit and foliage cleared to 50 cm around the trap captured significantly more flies than any other treatment using traditional 8 cm diameter traps. The only exception was the mid part of the season, where there were no differences among treatments.

For the mid, late, and post-harvest parts of the season, there were no significant differences in AMF captures among treatments for 12.5 cm spheres (25 cm out, 25 cm in, 50 cm out, 50 cm in). Overall, the 12.5 cm spheres captured significantly fewer AMF than 8 cm spheres for any position treatment. The only time when this was not the case was in mid-season. Similar to findings by Prokopy (1977), traditional 8 cm spheres proved more visually attractive to AMF than 12.5 cm sphere in all positions tested, as when fruit and foliage were pruned away to a distance of 50 cm and when traps were masked by shade in suboptimal positions within the canopy (inner canopy treatments).

Our results, as well as results from Drummond et al. (1984) and Rull and Prokopy (in press), suggest that clearing space around a red sphere trap to a radius of 50 cm does not decrease trap captures of AMF, and in fact may increase trap conspicousness (as measured by fly captures) to AMF. We found that overall, it is beneficial to clear fruit and foliage to a radius of between 25 and 50 cm around a trap, and that with all else being equal, it could be recommended to clear fruit and foliage to 50 cm because this would allow for fruit to grow substantially before it reaches within 25 cm of a trap. Such a practice would require less maintenance by a grower throughout the season. Ideally, more research should be done both in orchards that have a long history of grower management (i.e. pesticide sprays) and unmanaged orchards, to see what, if any, effect management history has on AMF captures on traps in different treatment positions. However, we are confident in recommending that odor-baited traps for direct control of AMF be positioned with fruit and foliage pruned to 50 cm around the trap; and that this should provide adequate protection of fruit from injury by AMF across the entire season.

3.5 Description of Figures and Tables

Fig. 3.1. Mean (+/- SEM) AMF captured per trap in Jersey Mac trees with fruit and foliage cleared to a radius of 0, 25, or 50 cm around the trap, for trap captures over the entire season, and for mid season, late season, and post-harvest alone. For each part of the season, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 3.2. Mean (+/- SEM) AMF captured per trap in Golden Delicious trees with fruit and foliage cleared to a radius of 0, 25, 50, 75, or 100 cm around the trap, for trap captures over the entire season, and for early, mid and late season alone. For each part of the season, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 3.3. Mean (+/- SEM) AMF captured per 8 cm trap in Jersey Mac trees when traps were either in the outer third of the canopy with fruit and foliage

cleared to 25 or 50 cm in a radius around the trap (termed 25 cm out and 50 cm out, respectively); or when traps were in the inner third of the canopy with fruit and foliage cleared to a radius of 25 or 50 cm around the trap (termed 25 cm in and 50 cm in, respectively). For each part of the season, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Fig. 3.4. Mean (+/- SEM) AMF captured per 12.5 cm trap in Jersey Mac trees when traps were either in the outer third of the canopy with fruit and foliage cleared to 25 or 50 cm in a radius around the trap (termed 25 cm out and 50 cm out, respectively); or when traps were in the inner third of the canopy with fruit and foliage cleared to a radius of 25 or 50 cm around the trap (termed 25 cm in and 50 cm in, respectively). For each part of the season, mean values superscribed by the same letter are not significantly different according to ANOVA and least significant difference tests (0.05 level).

Table 3.1. Difference between the mean number of AMF captured on 8 cm spheres and 12.5 cm spheres for each trap treatment (25 cm Out, 25 cm In, 50 cm Out, and 50 cm In), across the entire season and for the early, mid, and late part of the season alone. Asterisk denotes a significant difference between means according to a t-test (0.05 level).

3.6 Figures and Tables

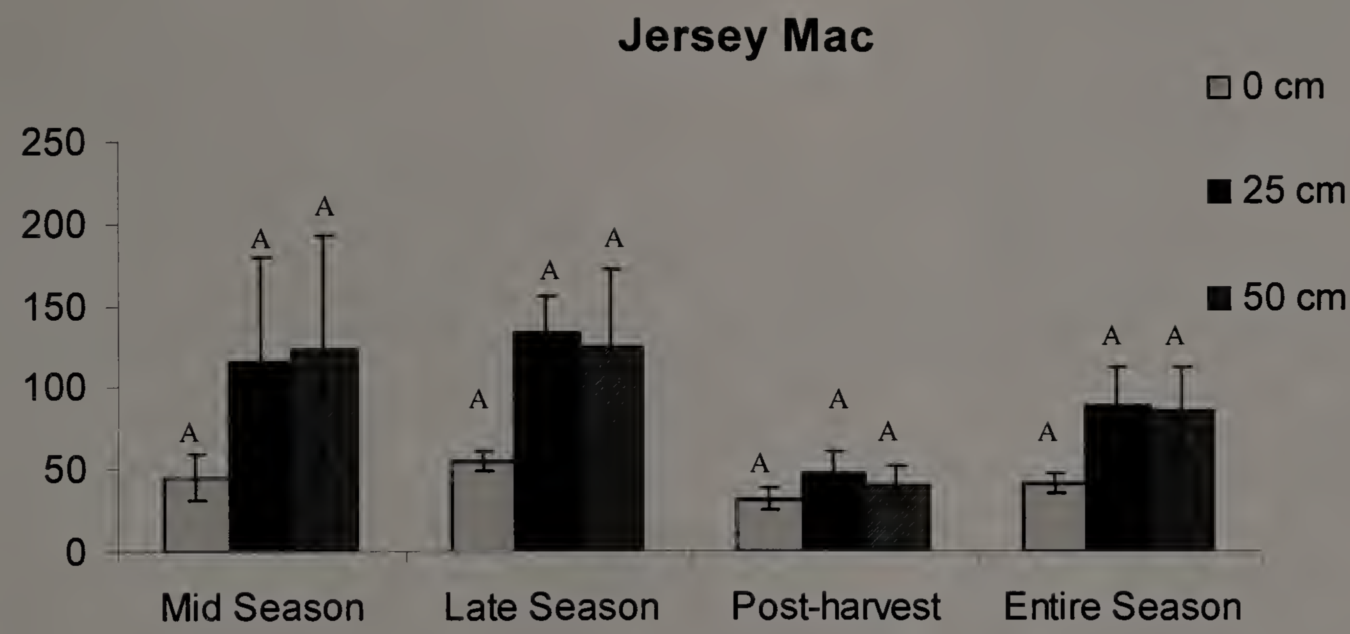


Fig. 3.1. AMF Captures: Jersey Mac Trees

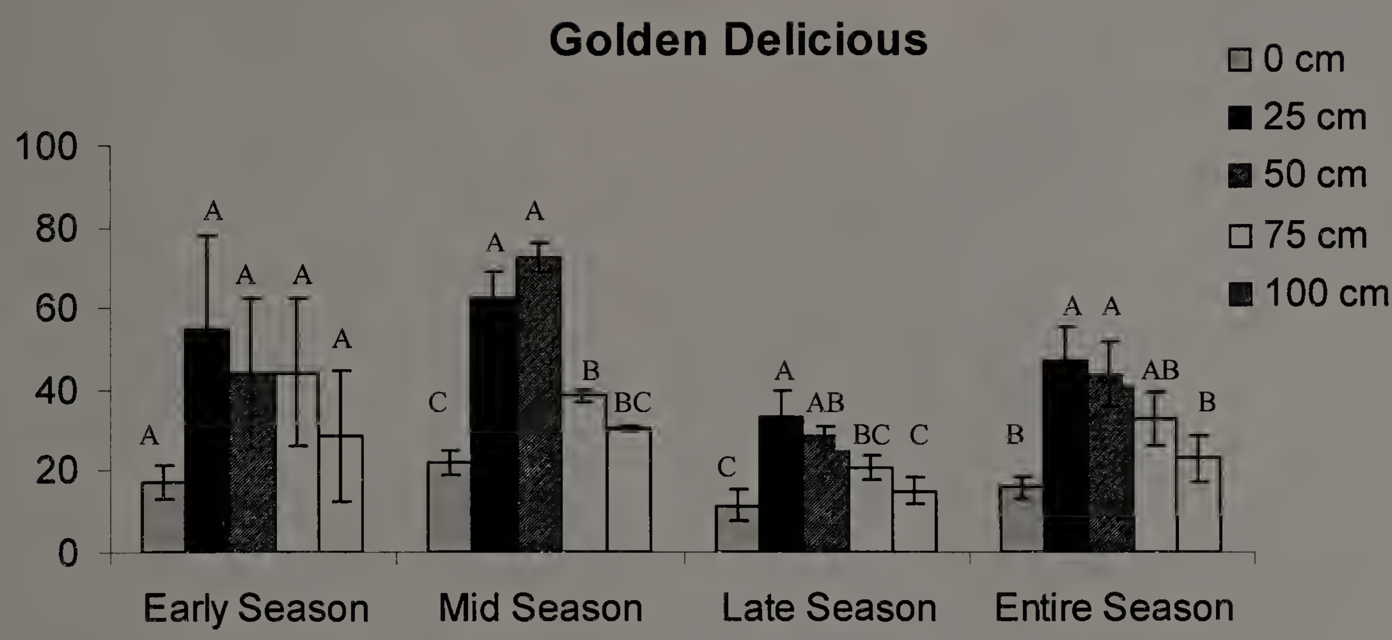


Fig. 3.2. AMF Captures: Golden Delicious Trees

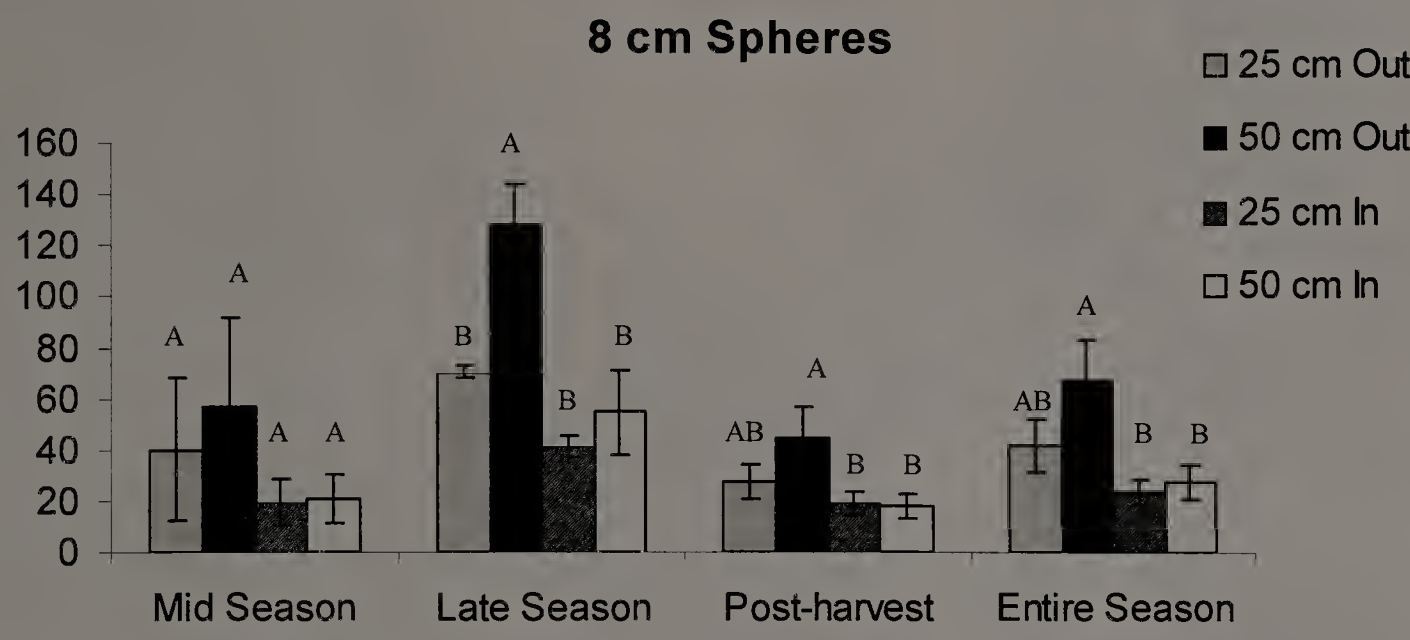


Fig. 3.3. AMF Captures: 8 cm Spheres

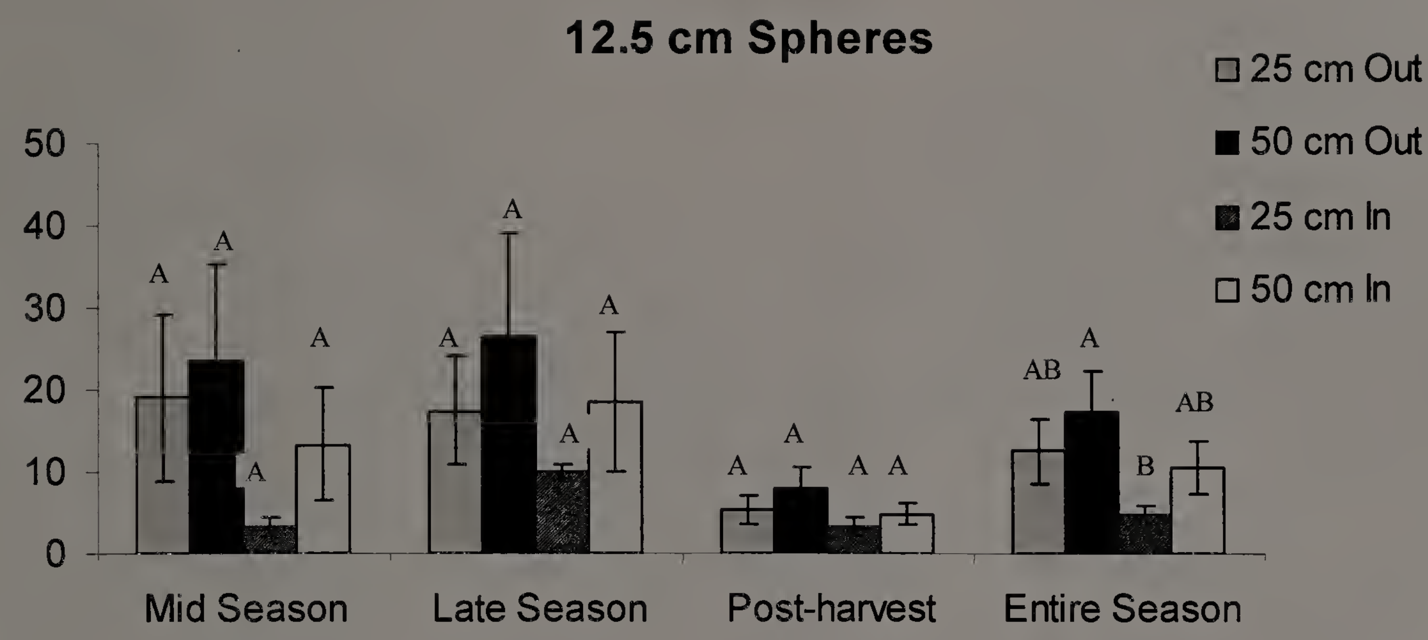


Fig. 3.4. AMF Captures: 12.5 cm Spheres

Table 3.1. Difference in Mean AMF Captures: 8 vs. 12.5 cm Spheres

	Mid Season	Late Season	Post-harvest	Entire Season
25 cm Out	21	53*	22.5*	28.77*
25 cm In	16.57	31*	15.5*	19*
50 cm Out	33	101*	36.5*	49.67*
50 cm In	7.67	36	13.25*	16.44*

REFERENCES

Aliniazee, M.T.; Mohammad, A.B.; Booth, S.R. (1987) Apple maggot (Dipt., Tephritidae) response to traps in an unsprayed orchard in Oregon. *Journal of Economic Entomol.* 80: 1143-1148

Aluja, M. & Prokopy, R.J. (1993) Host odor and visual stimulus interaction during intratree host finding behavior of *Rhagoletis pomonella* flies. *Journal of Chemical Ecology* 19: 2671-2696

Amman, G.D.; McGreggor, M.D.; Schmitz, R.F.; Oakes, R.D. (1988) Susceptibility of lodgepole pine to infestation by mountain pine beetles following partial cutting of stands. *Canadian Journal of Forest Research* 18(6): 688-695

Averill, A.L.; Reissig, W.H.; Roelofs, W.L. (1988) Specificity of olfactory responses in the tephritid fruit fly *Rhagoletis pomonella. Entomologia Experimentalis et Applicata* 47 (3): 211-222

Bentz, B.J.; Logan, T. A.; Amman, G.D. (1991) Temperature-dependant development of the mountain pine beetle (Coleoptera: Scolytidae) and simulation of its phenology. *Canadian Entomologist* 123(5): 1083-1094

Borden, J.H. (1989) Semiochemicals and bark beetle populations: exploitation of natural phenomena by pest management strategists. *Holarctic Ecology* 12: 501-510

Borden, J.H.; Chong, L.J.; Fuchs, M.C. (1983) Application of semiochemicals in post-logging manipulation of the mountain pine beetle, *Dendroctonus ponderosae*. *Journal of Economic Entomology* 76: 1428-1432

Bostanian, N.J.; & Racette, G. (2001) Attract and kill, an effective technique to manage apple maggot *Rhagoletis pomonella* in high density Quebec apple orchards. *Phytoprotection* 82: 25-34

Bostanian, N.J.; Vincent, C.; Chouinard, G.;& Racette, G. (1999) Managing apple maggot *Rhagoletis pomonella*, by perimeter trapping. *Phytoprotection* 80: 21-33

Bostanian, N.J.; Vincent, C.; Roy, M. (1993) Comparative effectiveness of three trap models to monitor the apple maggot, *Rhagoletis pomonella* (Walsh) (Dipt., Tephritidae), in Quebec. *Journal of Agricultural Entomolgy* 10: 73-82

Broumas, T.; Haniotakis, G.; Liaropoulos, C.; Tomazou, T.; Ragoussis, N. (2002) The efficacy of an improved form of the mass-trapping method for the control of the olive fruit fly, *Bactrocera (=Dacus) oleae* (Gmelin)(Diptera: Tephritidae): Pilot-scale feasibility studies. *Journal of Applied Entomology* 126(5): 217-223

Cardé and Bell eds. (1995) Chemical Ecology of Insects. Chapman and Hall, New York.

Cardé, R.T. & Minks, A.K. (1995) Control of moth pests by mating disruption: successes and constraints. *Annual Review of Entomology* 40: 559-585

Christie, M.; Prokopy, R.; Gamble, J.; Heckscher, D.; Mason, J. (1991) Effect of distance between traps on interception of apple maggot flies on perimeter apple trees. *Massachusetts Fruit Notes* 56: 18-19.

Cohen, H. and Yuval, B. (2000) Perimeter-trapping strategy to reduce Mediterranean fruit fly (Diptera: Tephritidae) damage to different host species in Israel. *J. Econ. Entomol.* 93 (3): 721-725.

Colvin, J. & Gibsen, G. (1992) Host-seeking behavior and management of tsetse. *Annual Review of Entomology* 37: 21-40

Dean, R.W. & Chapman, P.J. (1973) Bionomics of the apple maggot in eastern New York. Search Agric. (New York State, Geneva) 10: 1-64

Drummond, F.; Groden, E.; Prokopy, R.J. (1984): Comparative efficacy and optimal positioning of traps for monitoring apple maggot flies (Diptera: Tephritidae). Environmental Entomology 13: 232-235

Fadamiro, H.Y. & Baker, T.C. (2002) Pheromone puffs suppress mating by *Plodia interpunctella and Sitotroga cerealella* in an infested corn store. *Entomologia Experimentalis et Applicata* 102(3): 239-251

Fein, B.L.; Reissig, W.H.; Roelofs, W.L. (1982) Identification of apple volatiles attractive to the apple maggot, *Rhagoletis pomonella. J. Chem. Ecol.* 8(12): 1473-1488.

Finch, S. & Collier, R.H. (2000) Host-plant selection by insects- a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. *Entomologia Experimentalis et Applicata* 96: 91-102

Foster, S.P. & Harris, M.O. (1997) Behavioral manipulation methods for insect pest management. *Annual Review of Entomology* 42: 123-146

Glass, E.H.; Lienk, S.E. (1971) Apple insect and mite populations developing after discontinuance of insecticides: 10 year record. *J. Econ. Entomol.* 64: 23-26.

Gould, F. (1991) Arthropod behavior and the efficacy of plant protectants. *Annual Review of Entomology* 36: 305-330

Green, T.A.; Prokopy, R.J.; Hosmer, D.W. (1994) Distance of response to host tree models by female apple maggot flies, *Rhagoletis pomonella*: interaction of visual and olfactory stimuli. *J. Chem. Ecol.* 20: 2393-2413.

Haniotakes, G.; Francke, W.; Mori, K.; Redlich, H.; Schurig, V. (1986) Sex-specific activity of (R)-(-)-and (S)-(+)- 1,7-dioxaspiro[5.5] undercane, the major pheromone of *Dacus oleae*. *Journal of Chemical Ecology* 12: 1559-1568

Haniotakes, G.; Kozyrakes, M.; Fitsakes, T.; Antonidake, A. (1991) An effective mass-trapping method for the control of *Dacus oleae* (Diptera: Tephritidae). *Journal of Economic Entomology* 84:564-569

Harris, M.O. & Foster, S.P. (1995) Behavior and integration. In Chemical Ecology of Insects 2. eds. Carde, R.T. & Bell, W.J. Chapman and Hall, New York.

Hokanen, H.M.T. (1991) Trap cropping in pest management. *Annual Review of Entomology* 36: 119-138

Kelsey, R.G. (1994) Ethanol and ambrosia beetles in Douglas fir logs with and without branches. *Journal of Chemical Ecology* 20: 3307-3319

Kelsey, R.G. & Joseph, G. (1999) Ethanol and ambrosia beetles in Douglas fir logs exposed of protected from rain. *Journal of Chemical Ecology* 25: 2793-2809

Lindegren, B.S. (1990) Ambrosia beetles. *Journal of Forestry* 88: 8-11

Logan, J.A.; & Bentz, (1999) Model analysis of mountain pine beetle personality. *Environmental Entomology* 28: 924-934

Mazomenos, B.E. & Haniotakes, G. (1981) A multicomponent female sex pheromone of *Dacus oleae*. Isolation and bioassay. *Journal of Chemical Ecology* 7: 53-60

McLean, J.A. & Borden, J.H. (1977) Suppression of *Gnathotrichus sulcatus* with sulcatol-based traps in a commercial sawmill and notes on the occurrence of *G. retusus* and *Trypodendron lineatum*. *Canadian Journal of Forestry* 7: 348-356

Mithcell, R.G.; Waring, R.H.; Pitman, G.B. (1983) Thinning lodgepole pine (*Pinus contorta*) increases tree vigor and resistance to mountain pine beetle (*Dendroctonus ponderosae*). *Forest Science* 29(1): 204-211

Owens, E.D. and Prokopy, R.J. (1984) Habitat background characteristics influencing *Rhagoletis pomonella* (Walsh) (Dipt., Tephritidae) fly response to foliar and fruit mimic traps. *Journal of Applied Entomol.* 1: 98-103

Phillips, A.D.G. & Wyatt, T.D. (1992) Beyond origami: using behavioral observations as a strategy to improve trap design. *Entomologia Experimentalis et Applicata* 62: 67-74

Prokopy, R.J. (1968) Visual responses of apple maggot flies: *Rhagoletis pomonella*; orchard studies. *Entomologia Experimentalis et Applicata* 11: 403-422

Prokopy, R.J. (1975) Apple maggot control by sticky red spheres. *Journal of Insect Behavior* 68: 197-198

Prokopy, R.J. (1977) Attraction of *Rhagoletis* flies (Dipt. Tepritidae) to red spheres of different sizes. *Canadian Entomologist* 109: 593-596

Prokopy, R.J.; Cooley, S.S.; Prokopy, J.J.; Quan, Q.; Buornaccorsi, J.P. (1994) Interactive effects of resource abundance and state of adults on residence of apple maggot flies in host tree patches. *Environmental Entomology* 23: 304-315

Prokopy, R.J.; Johnson, S.A.; & O'Brien, M.T. (1990) Second-stage integrated management of apple arthropod pests. *Entomologia Experimentalis et Applicata* 54: 9-19

Prokopy, R.J. & Kogan, M. (2002) Integrated pest management. In Encyclopedia of Insects, ed. Resh, V.H. & Carde, R.T., in press, Academic Press, New York.

Prokopy, R.J. and Mason J. (1996) Behavioral control of apple maggot flies. Fruit Flies of Economic Importance. In McPheron, B. and Steck, G. (Eds): 555-559. St. Lucie Press, Delray Beach, FL.

Prokopy, R.J.; Mason, J.L.; Christie, M.; Wright, S.E. (1996) Arthropod and natural enemy abundance under second-level verses first-level integrated pest management practices in apple orchards: a 4-year study. *Agric. Ecosyst. Environ.* 57: 35-47.

Prokopy, R.J.; Mason, J.; Wright, S.E.; Cooley, D.R.; Autio, W.R. (1995) Second-level IPM for pests in apple orchards: performance according to cultivar type. *Fruit Notes* 60: 11-13

Prokopy, R.J.; Mittenthal, R.E.; Wright, S.E. (2003) Evaluation of trap deployment patterns for behavioural control of apple maggot flies (Dipt., Tephritidae). *J. Appl. Entomol.* 127: 276-281.

Prokopy, R.J. & Roitberg, B.D. (2003) Arthropod pest behavior and IPM. In Press.

Prokopy, R.J.; Wright, S.E.; Black, J.L.; HU, X.P.; McGuire, M.R. (2000) Attracticidal spheres for controlling apple maggot flies: commercial-orchard trials. *Entomologia Experimentalis et Applicata* 97: 293-299

Prokopy, R.J.; Wright, S.E.; Black, J.L.; & Rull, J. (2001) Size of orchard trees as a factor affecting behavioral control of apple maggot flies by traps. *Journal of Applied Entomology* 125: 371-375

Raffa, K.F. (2001) Mixed messages across multiple trophic levels: the ecology of bark beetle chemical communication systems. *Chemoecology* 11, 49-65

Reissig, H.W. (1974) Field test of the response of *Rhagoletis pomonella* to apples. *Environmental Entomology* 3: 733-735

Ressig, W.H.; Fein, B.L.; Roelofs, W.L. (1982) Field tests of synthetic apple volatiles as apple maggot attactants. *Environmental Entomology* 11: 1294-1298

Roitberg, B.D. & Prokopy, R.J. (1984) Host visitation sequence as a determinant of search persistence in fruit parasitic tephritid flies. *Oecologia* 62: 7-12

Roitberg, B.D.; Van Lenteren, J.C.; Van Alphen, J.J.M.; Galis, F.; Prokopy, R.J. (1982) Foraging behavior of *Rhagoletis pomonella*, a parasite of hawthorn (*Crataegeus viridis*) in nature. *Journal of Animal Ecology* 51, 307-325

Rull, J. and Prokopy, R.J. (2000) Attraction of apple maggot flies, *Rhagoletis pomonella* (Dipt., Tephritidae) of different physiological states to odour-baited traps in the presence and absence of food. *Bulletin of Entomology Research* 90: 77-88

Rull, J. & Prokopy, R.J. (2001) Effect of apple-orchard structure on interception of *Rhagoletis pomonella* (Diptera: Tephritidae) flies by odor-baited traps. *Canadian Entomologist* 133: 355-363

Rull, J. & Prokopy, R.J. (2003) Trap position and fruit presence affect visual responses of apple maggot flies (Dipt., Tephritidae) to different trap types. *Journal of Applied Entomol.* 127, 85-90

Rull, J. and Prokopy, R.J. (2003) Revisiting within-tree trap positioning for apple maggot fly (Dipt., Tephritidae) behavioral control. *Journal of Applied Entomol.* In press.

Torr, S.J. (1989) The host-oriented behavior of tsetse flies (*Glossina*): the interaction of visual and olfactory stimuli. *Physiological Entomology* 14: 325-340

Vale, G.A.; Lovemore, D.F.; Flint, S.; Cockbill, G.F. (1988) Odour-baited targets to control tsetse flies, *Glossina spp.*, in Zimbabwe. *Bulletin of Entomological Research* 78: 31-49

Vale, G.A. (1998) Responses of tsetse flies to vegetation in Zimbabwe: implications for population distribution and bait sitting. *Bulletin of Entomological Research* 78: 31-49

Vreysen, M.J.; Salah, K.M.; Ali, M.Y.; Abdulla, A.M.; Zhu, K.G.; Dyck, V.A.; Msangi, A.R.; Mkonyi, P.A.; Feldman, H.U. (2000) *Glossina austene* (Diptera: Glossinidae) eradicated on the island of Unguja, Zanzibar using the sterile insect technique. *Journal of Economic Entomology* 93(1): 123-135

Zhang, A.; Linn, C.; Wright, S.; Prokopy, R.J.; Reissig, H.; Roelofs, W. (1999) Identification of a new blend of apple volatiles attractive to the apple maggot *Rhagoletis pomonella*. *Journal of Chemical Ecology* 25: 1221-1232