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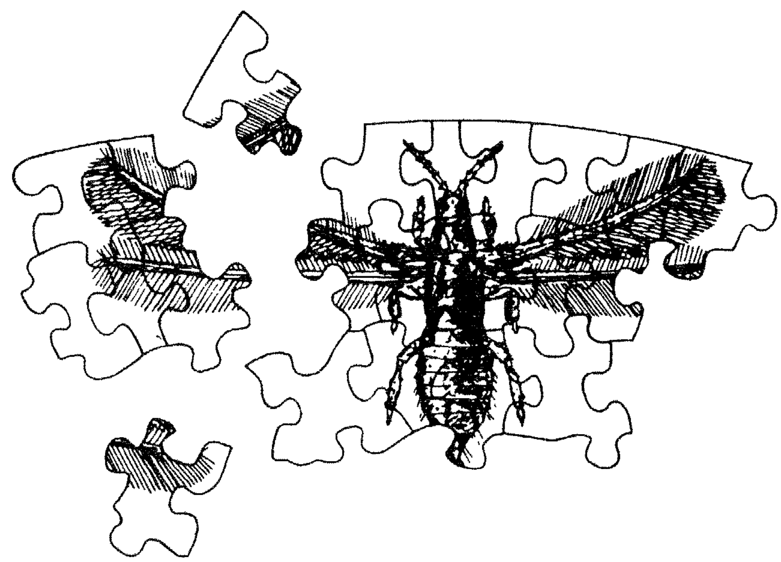
Towards Understanding Thysanoptera



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ACKNOWLEDGMENTS

This conference would not have been possible without the dedicated efforts of many people, only a few of whom can be mentioned here. We thank Steve LaRosa for organization of special events and Eva Noronha-Doane for facilitating registration. Recording of the conference was expertly supervised by Luke Curtis; transcriptions were prepared by Peggy Verville and Nancy Burgess from the University of Vermont, Department of Plant and Soil Science; and layout of the proceedings was prepared by Frances Birdsall. Thanks also to the numerous personnel from the Vermont Department of Forests, Parks and Recreation who helped with transportation and many other technical details.

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TOWARDS UNDERSTANDING THYSANOPTERA

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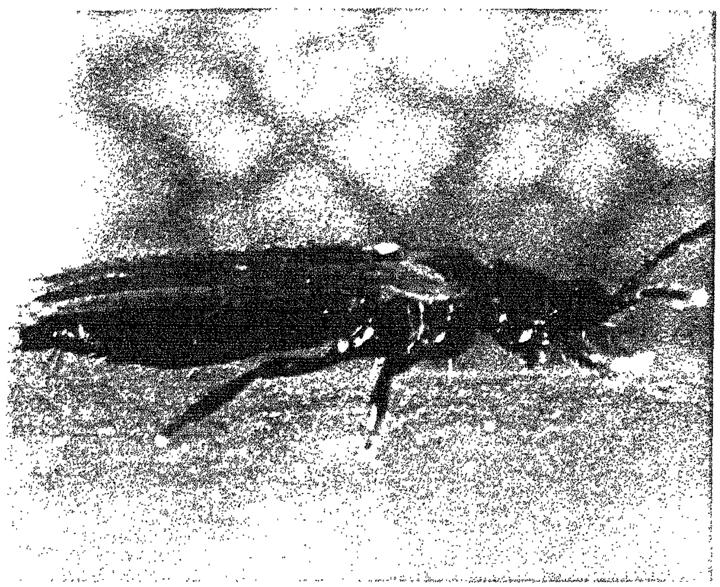
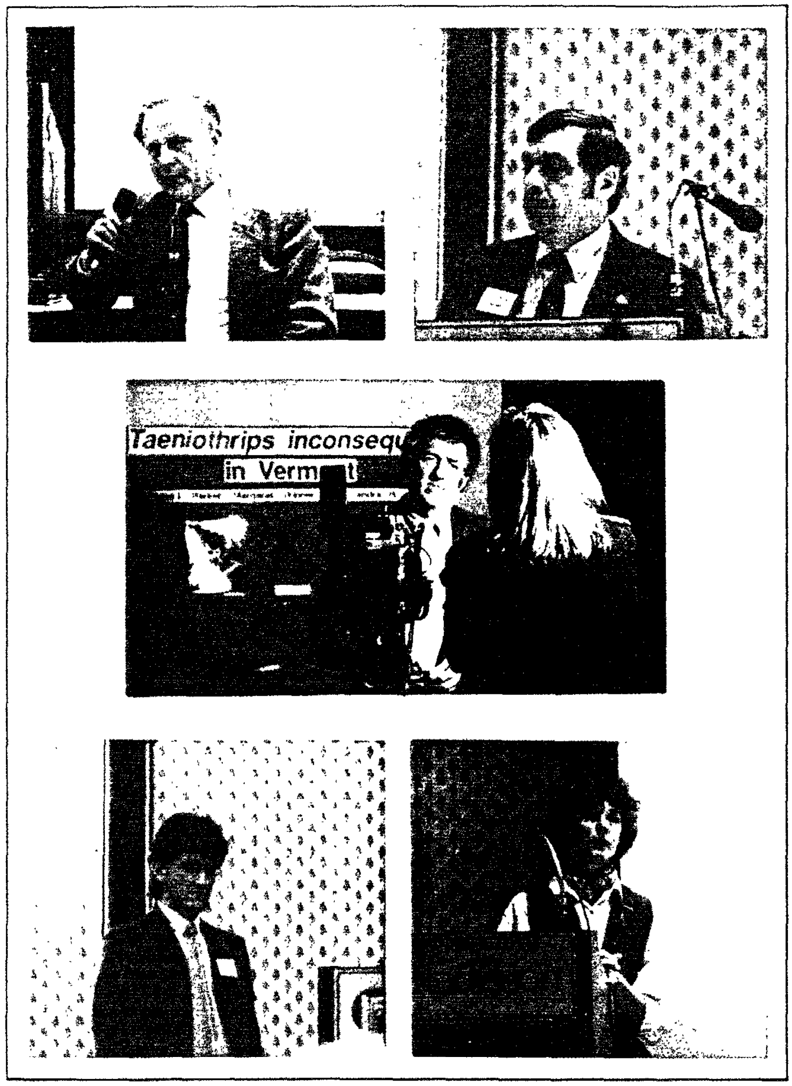


PEAR THRIPS, *Taeniothrips inconsequens* (Uzel)
(photo by T. E. Downer)



A few of the conference participants (from top left to bottom right): Trevor Lewis, Institute of Arable Crops Research; Conrad Motyka, VT Department of Forests, Parks and Recreation; Bruce L. Parker, The University of Vermont; Nick J. Mills, Commonwealth Institute of Biological Control; Margaret Skinner, The University of Vermont.

PREFACE

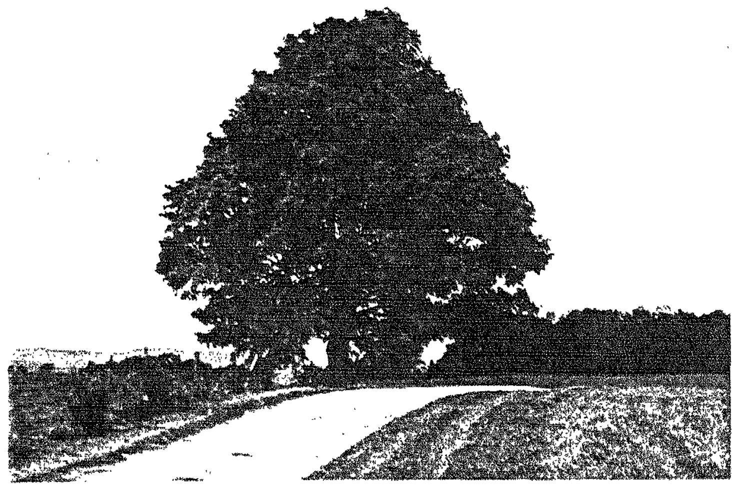
Pear thrips, *Taeniothrips inconsequens (Uzel)*, first surfaced as a pest of sugar maple, *Acer saccharum* Marsh, in Pennsylvania in the late 1970s. Though similar damage was observed in Vermont in the early 1980s, it was probably misdiagnosed as frost damage until 1985, when finally thrips were positively confirmed as the causal agent. Pear thrips damage to sugar maple fluctuated greatly from year to year, raising only slight concern among sugarmakers and forest managers. However, the situation changed dramatically in the spring of 1988, when pear thrips caused widespread, severe foliage damage to sugar maple in southern Vermont (over 200 thousand hectares) and other New England States. Recognized as a potential threat to forest health, pear thrips received tremendous media coverage, including the front page of the New York Times and the CBS Evening News!

The response in Vermont to this crisis was swift. With support from the Vermont legislature and the Department of Agriculture, a major research effort was launched, coordinated jointly by the University of Vermont and the VT Department of Forests, Parks and Recreation. This pest presented unique research and management challenges. Pear thrips on sugar maple represented a known pest on a new host in a new habitat. As of 1988 almost no information existed on this insect in a sugar maple forest. In addition thrips in general were virtually unknown as a northern hardwood forest pest, and forest managers knew little about how to handle such an insect. Finally, because thrips are such small insects, new and specialized methods were needed for survey and study of this pest.

As Vermont's research efforts got underway, it became clear that much could be learned from scientists familiar with other thrips species. The goal of this conference was to gather these specialists together to present their ideas on thrips survey and management methodology, particularly as it related to pear thrips in a forest setting. Participants came from across the United States, Canada and the United Kingdom to share their expertise. Though many didn't know that a "sugarbush" was not a shrub, but a natural stand of mature 30-m-tall sugar maple trees (100 ft), they all knew what maple syrup was! Certainly by the end of the conference all of the participants recognized the unique value of the sugar maple to the heritage and economy of Vermont and the Northeast, and shared our concern for its future in light of the threat of pear thrips.

We thank all of the conference participants who freely and enthusiastically shared their knowledge. Without their expertise and continued technical support, our pear thrips research would not have progressed as far or as fast as it has. We thank all those attending the conference for helping to make it a productive event. Though the pear thrips problem is far from being "solved," this conference started the research process on a solid footing.

INTEGRATED PEST MANAGEMENT



Sugar Maple, *Acer saccharum* Marsh.
(photo by D. Lockhart)

INTEGRATED PEST MANAGEMENT AND THE PEAR THRIPS

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Although it is a pleasure to be here, our primary reason for being here is far from pleasant. During the last ten years, we have had serious problems with the gypsy moth, western spruce budworm, southern pine beetle, mountain pine beetle, fusiform rust and root diseases and the worst spruce budworm epidemic ever recorded. Just when these outbreaks have largely subsided, a new pest rears it's ugly head in our Nation's forests.

These outbreaks, coupled with publicity about acid rain, air pollution, and global warming have influenced many Americans to perceive that there has been a rather dramatic decline in the health of our Nation's forests.

Has there been a precipitous decline in the health of our forests? Are our forests unhealthy? Recently, a task force within the Forest Service looked at the rate of tree mortality on commercial forest land as one indicator of forest health. Here in the North, growing stock mortality as a percentage of growing stock inventory in northern softwood and hardwood forests has remained stable except for a slight increase during the years 1952 to 1976 (due primarily to the spruce budworm outbreak), returning to approximately the 1952 rates after 1976. Nationally, modest decreases in softwood and hardwood growing stock mortality as a percentage of growing stock inventory have actually occurred between 1952 and 1987. The data show that, in general, mortality is increasing, but that annual growth is increasing even faster.

These figures do not indicate that a nationwide forest health crisis is at hand. However, serious local and regional problems exist. For example, in the South, softwood growing stock mortality as a percentage of growing stock inventory jumped significantly after 1976, primarily as a result of southern pine beetle outbreaks that occurred during the period.

In addition to some serious local and regional pest problems, we know that our forest land base is shrinking. In 1977, forests covered over 31 percent of the 1 billion hectares (2.4 billion acres) of land and water area in the United States. By the year 2030, the amount of land classified as forest is expected to decrease by about 9.7 million hectares (24 million acres) as other land uses take precedence. Most losses of forest land are expected to occur on the more productive sites at lower elevations where accessible land will be acquired for agricultural, industrial and urban development. The remaining forests will have to supply a greater proportion of goods and services.

To protect our forests from pests, we must use all the tools we have available. Managers must move from reactive to proactive strategies. This will mean greater emphasis on prevention and less dependency on suppression to reduce the impact of forest pests.

Integrated pest management, or IPM, is the best tool that we, as land managers, have available to assist in managing the forest. Integrated pest management is a much used and poorly understood concept in forest protection. IPM is defined in a Forest Service Handbook as: "a decision-making and action process incorporating biological, economic and environmental evaluation of pest-host systems to manage pest populations." There are other definitions of IPM and each of you probably has your own working definition. Nevertheless, certain components seem to be common to most definitions of IPM.

In forestry, IPM is a strategy for long-term management of forest pest-host interactions. Situations potentially capable of causing pest problems are anticipated and avoided or changed before outbreaks occur. IPM includes intensive surveys that provide early pest detection and delineation information. IPM includes introduction, augmentation and/or conservation of predators, parasites or pathogens that help keep pest populations at low levels. And IPM includes intervention with appropriate techniques to prevent or disrupt damage-causing behavior or successful pest reproduction. IPM also considers the condition of trees and forests, their tolerance to pest effects, and their resilience in being able to recover from pest outbreaks.

Unfortunately, IPM is often erroneously promoted as an alternative to chemical insecticides. All too frequently, interest in IPM occurs only after pest populations have reached damaging levels. As land managers we understandably look for quick, efficient and cost-effective solutions. We may consider a series of options among which is an IPM approach that includes the use of a pesticide to control outbreak populations. The IPM option is selected, pesticide is applied and the pest outbreak subsides. But other components of the IPM option are often abandoned. Long-term benefits are not achieved because of the failure to implement all components of the IPM option.

Silviculture is, in the long run, the most powerful component of IPM that we, as forest managers, have to mitigate the impact of forest pests and atmospheric pollution on the condition of the forest. Silvicultural practices, such as site preparation, planting, prescribed fire, thinning, control of competing vegetation, and various harvesting practices, including regeneration cutting, commercial thinning and salvage, can have highly beneficial effects on forest vegetation, if applied properly and in a timely fashion. Other practices, such as the use of genetically-improved seedlings, also offer opportunities to grow forests that are more resistant to insects, diseases and pollution.

In my mind, truly integrated pest management must be accomplished through forest management prescriptions which accomplish the long-term goal of minimizing pest impacts. This means including the technical pest management information needed in the resource management decision-making process. And this technical information must be in a form that is compatible with and meets the needs of the planning and decision-making process and is ecologically sound.

Many of the people in this room have worked together in the past. The Vermont Hardwood Tree Health Survey, the North American Sugar Maple Decline Project and the Vermont IPM Spruce Budworm Demonstration Project are just a few examples of successful cooperative efforts that we have undertaken together.

I feel confident that this conference will be a great help in developing an integrated pest management system for pear thrips that will meet short-term needs for protection as well as long-term goals for prevention. It is this kind of team approach that will most effectively address the problems posed by a new pest like the pear thrips.

HERBIVORY BY *Thrips tabaci*

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Herbivory by *Thrips tabaci* (Lindeman) affects both the bulb yield and phytohormone balance in its major host plant, the onion (*Alium cepa* L.). Seasonal changes in the susceptibility of onion yield to *T. tabaci* feeding were examined during the three growth stages of onion; prebulbing, bulbing and sizing (Kendall & Capinera 1987). The prebulbing stage is characterized by rapid leaf initiation. Increased bulb size and decreased leaf initiation occurs during bulbing. Further bulb growth and collapse of the leaf bundle characterizes the sizing stage.

Thrips feeding also stimulates increased production of the phytohormone ethylene which affects the physiology of the plant. Ethylene is responsible for a wide variety of effects including fruit ripening and leaf senescence (Abeles 1973). On the biochemical level, ethylene is a secondary messenger responsible for the production of defensive compounds in plants (Yang & Pratt 1978). Our objective was to distinguish mechanical induction of ethylene evolution from enhanced production associated with thrips feeding (Kendall & Bjostad 1989).

Materials and Methods

Susceptibility of Onion Growth Stages

Two field studies (1982 and 1983) and one greenhouse study (1984) were conducted. In order to assess seasonal changes in the susceptibility of the onion to herbivory, thrips populations were allowed to build up to specific densities only within each growth period. Onions were sprayed with diazinon during the remaining growth stages. Weekly estimation of thrips densities per plot was determined by visual examination. Yield measurements were conducted 30-60 days after harvest. Bulb weights (50 onions per plot) were measured to the nearest 0.1 g on an electronic balance (Fisher 250). BMDP was used to analyze the regression analyses. For further detail see Kendall & Capinera (1987).

Ethylene Production

One-time mechanical damage (Experiment 1). Glass tubes (23 ml) fitted with rubber septa were placed over onion plants, and weather-stripping putty (Mortite) was secured to the bottoms to prevent contact with the soil. The onions were treated in one of two ways: twenty second-instar thrips larvae were introduced or twenty 2 mm incisions were made with a sterile 00 insect pin. Control plants were left undamaged and empty control tubes were included to check for the presence of ethylene in the collection system. Tubes were stoppered with rubber septa and allowed to incubate for 48 hours. Sample size consisted of four plants per treatment. After 24 and 48 hours, ethylene analysis was performed, yielding eight ethylene readings each for uninfested, infested, and mechanically damaged tissues. After the 48-hour reading, plants were weighed to the nearest hundredth of a milligram. After 24 hours a 1-ml gas sample was withdrawn from the headspace of each vial using a pressure-lok syringe, and analyzed for ethylene. A model 5890 Hewlett-Packard gas chromatograph equipped with a flame-ionization detector, and a Hewlett-Packard model 3390A integrator recorder were used in the analysis.

Semi-continuous mechanical damage (Experiment 2). To more closely approximate the continuous feeding damage exhibited by thrips, intact plants were wounded every 12 hours with a sterile 00 insect pin attached to a wire entering the septum. In this manner, damage could be inflicted without opening the tubes. A piece of wire was also inserted into the septa of the remaining tubes. Experimental design was identical to the previous experiment. Sample size consisted of four plants per treatment. Readings were taken after 14, 16, 19, 36, 39, 42, 60, 72, 84, and 94 hour incubation times. After 96 hours, the plants were dried and weighed to the nearest hundredth of a milligram. The wounds were measured to the nearest hundredth of a millimeter.

Thrips extract (Experiment 3). Thrips were placed in a sterile saline solution and macerated into a thick paste. An extract of ten thrips was placed in each of ten 5 mm wounds made with a sterile 00 insect pin. Mechanically damaged plants were treated in an identical manner to those with the thrips extract, except only sterile saline solution was placed in the wounds. A third of the plants remained unwounded. Sample size consisted of four plants per treatment. Readings were taken every 12 hours for 96 hours. After 96 hours, the plants were dried and weighed and the wounds were measured as described previously.

Statistical Analyses

All data were analyzed by one-way analysis of variance using BMDP. For further detail see Kendall & Bjostad (1989).

Results

Susceptibility of Onion Growth Stages

A significant relationship between thrips numbers and yield was not found during the pre-bulbing or sizing stages. During the bulbing stage, a significant negative relationship between thrips numbers and bulb size was observed (Fig. 1). Similar results were obtained for the 1983 field season and the 1984 greenhouse study (Kendall & Capinera 1987).

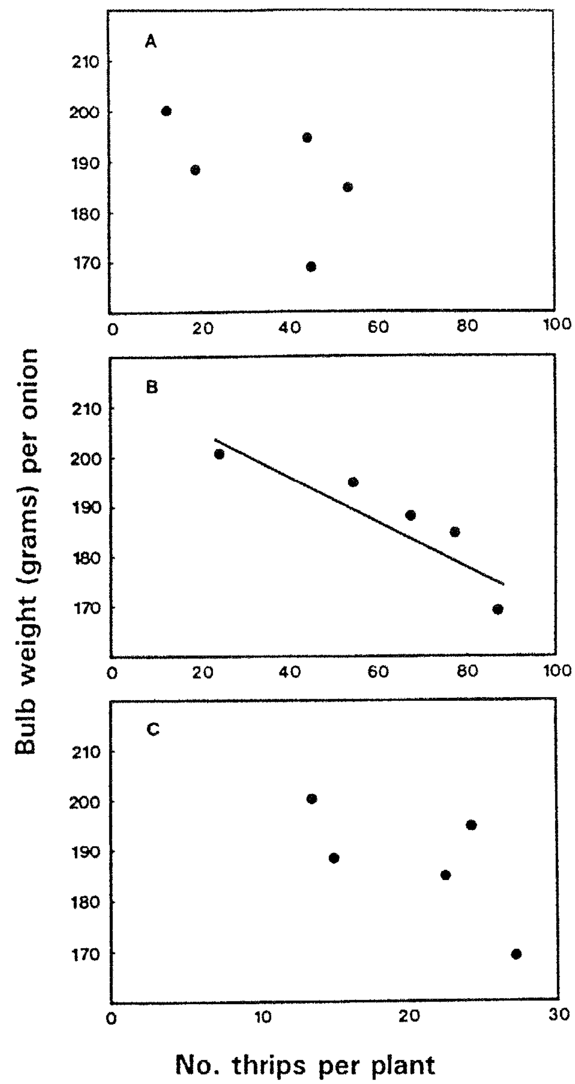

Figure 1. Effect of thrips herbivory on bulb size in 1982: (A) prebulbing ($P > 0.05$), (B) bulbing, $r^2 = 0.81$ ($P < 0.05$), (C) sizing ($P > 0.05$) (Kendall & Capinera 1987).

Ethylene Production

In the first experiment, thrips-infested tissue produced significantly greater ethylene compared to uninfested plants and to foliage that was mechanically damaged at the beginning of the experiment (Table 1). Ethylene evolution from mechanically damaged and unwounded plants was not significantly different ($P < 0.05$) (Table 1). In Experiment 2 significant differences existed between thrips-infested and semi-continuous mechanically-wounded plants and to unwounded foliage from 19 to 96 hours incubation time (Fig. 2).

Table 1. Ethylene production from infested, uninfested and mechanically wounded intact onion plants

Incubation	Ethylene production (pmole/g)*		
Hours	Infested	Mechanically wounded	Unwounded
24	14.87 ± 3.33a	4.59 ± 0.96b	4.50 ± 0.69b
48	21.27 ± 5.10a	5.23 ± 1.00b	3.64 ± 1.23b

* Mean and standard errors.

Means followed by the same letter in one row are not significantly different (Duncan's Multiple Range Test, $P \leq 0.05$).

Mechanically-wounded and unwounded plants did not produce significantly different levels of ethylene (Fig. 2). The third experiment produced similar results. Plants inoculated with thrips extract produced significantly greater levels of ethylene than mechanically-wounded and unwounded foliage from 60 to 96 hours incubation time (Fig. 3). Ethylene evolution from mechanically damaged and unwounded plants was not significantly different ($P < 0.05$) (Fig. 3).

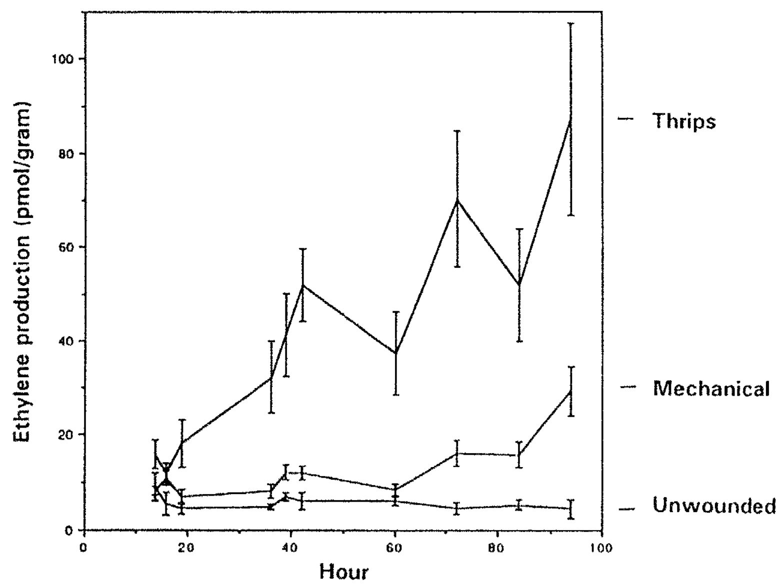

Figure 2. Ethylene production from thrips infested, semi-continuously mechanically-wounded, and unwounded intact onion plants. Vertical lines depict standard errors for the mean (Kendall & Bjostad 1989).

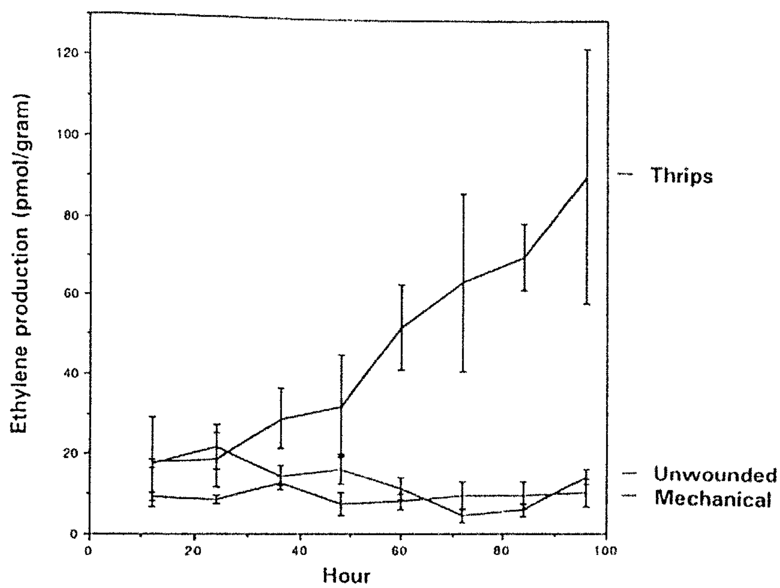

Figure 3. Ethylene production from plants inoculated with thrips extract, mechanically-wounded plants, and unwounded foliage. Vertical lines depict standard errors for the mean (Kendall & Bjostad 1989).

Discussion

Susceptibility of Onion Growth Stages

Growth stages of the onion exhibit differential responses to feeding by *T. tabaci*. The prebulbing and sizing stages are relatively insensitive to herbivory, but the bulbing stage is highly susceptible. During bulbing, nutrients from the foliage are shunted into the bulb which acts as a resource sink. If nutrients are removed from the foliage at this time, bulb weight will be reduced (Kendall & Capinera 1987). Management practices should concentrate on protection of this highly susceptible growth stage. The growth stages of many plant species exhibit similar responses to herbivore pressure (Bardner & Fletcher 1974). The maple may also exhibit seasonal changes in susceptibility to pear thrips.

Ethylene Production

Thrips feeding induced significantly greater ethylene evolution that would be expected from mechanical damage alone, presumably because thrips introduce cues during feeding that induce ethylene production by the plant. Because mechanical damage is directly proportional to ethylene production, measurement of ethylene evolution from maple trees may represent a novel, relatively simple and inexpensive technique to quantitatively assess defoliation injury in maples.

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AERIAL SPRAY TECHNOLOGY: POSSIBILITIES AND LIMITATIONS FOR CONTROL OF PEAR THRIPS

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Abstract

The feasibility of using aerial application as a means of managing a pear thrips infestation in maple forest stands is examined, based on existing knowledge of forest aerial application acquired from theoretical and empirical studies. Specific strategies by which aerial application should be performed and potential problem areas are discussed. Two new tools, aircraft characterization equipment and an aerial spray program mission planning computer software package are briefly described as examples of technology transfer which have been used to improve aerial applications in forests.

Introduction

This paper examines the feasibility of using aerial application as a means of dealing with the infestation of pear thrips in maple forest stands. It approaches the problem from theoretical and empirical standpoints based on knowledge that has been acquired on aerial application and suggests specific ways in which aerial application should be performed. No presumption is made that this is necessarily the correct approach, nor that it should be done in isolation, without integrated pest management considerations. Aerial application spray trials of specific insecticides for pear thrips management have been performed by others, and will be reported during this conference (H. B. Teillon & B. L. Parker, this publication).

To use an insecticide effectively for controlling a pest, the following facts should be known: (1) the distribution and behavior of the susceptible stage of the pest in space and time, (2) the approximate lethal dose required, (3) an efficient way of ensuring that an adequate number of toxic doses are deposited on the biological target with minimum contamination of non-target biomass.

Little is known about the behavior of pear thrips, *Taeniothrips inconsequens* (Uzel). However it would appear that the most vulnerable stage of the insect is the adult female, which emerges from the ground at the time of bud break, and flies to the bud. The timing of an application of pesticide would need to be exact to assure that the presence of a lethal concentration of insecticide coincides with the entry of the adult into the bud. Control of later larval stages that feed on newly expanded leaves would give a longer time frame. Once the biological target has been defined, in terms of its location, growth stage and timing, it is necessary to examine ways by which the insecticide can be applied with minimum drift outside the area of treatment. It is the definition of the methods that are used to optimize this process which are the subject of this paper.

Objectives

- To examine and define possibilities and limitations of aerial application for controlling pear thrips.

- To approach the above question by extrapolating from existing knowledge of aerial application in broad-leafed and coniferous forests, and from theoretical considerations.

- To review available tools that provide aerial application projects with aircraft spray pattern assessment and computer planning and operation costs.

Insecticide Application Considerations

Target definition. When the adult pear thrips emerges from the ground, she is thought to fly to the tree buds directly, probably settling on several twig sites before reaching her final destination. The insect then squeezes her way into the bud, where feeding takes place. It is thought that the female exhibits considerable exploratory behavior, moving around the bud before she commences her entry. The most likely ideal target therefore would be the bud and adjacent twig. The bud would have to be sprayed before the adult female enters it; the adult would have effective protection from the insecticide after entering the bud, unless a systemic pesticide was used. To enable reasonable planning for a spray project and unexpected changes in weather, the areas would have to be sprayed up to a week before the known likely emergence date. Therefore an insecticide with some degree of residual action would have to be used.

Toxic dose. Carbaryl (Sevin) is one of the few insecticides approved for spraying in maple forests. The LC_{95} of carbaryl is not known for pear thrips, but for the purpose of this paper has been conservatively assumed to be between 10 and 100 ppm. This figure can be used to calculate the number of LD_{95} doses in a range of droplet sizes typically produced by commercial spray equipment. These estimated numbers of toxic doses can then be used in guidance of the selection of spray parameters, namely the application rate and droplet size to be used in the control.

Delivery of pesticide. The accurate delivery of pesticide to broad leaves or pine needles in forest stands is one of the most challenging problems facing the forest pest manager. The factors limiting such accurate application have been summarized (Ekblad & Barry 1983).

Although a few studies of foliage deposition have been made on broad-leafed forests (Yendol et al. 1990), and a larger number on pine forests, no comprehensive studies exist on aerial application projects made on broad-leafed trees before leaf expansion. Orchard spraying is commonly done on leafless trees, but the technique used involves very high application rates on short trees with ground sprayers, and bears little relevance to the situation being considered here.

It is therefore necessary to systematically examine the process of capture of droplets by targets the size of maple tree buds in order to get an indication of how to approach the aerial application problem.

Droplet size considerations. When sprays are aerially applied 15 m (50 ft) above a forest canopy, two kinds of off-target deposition may occur. Large droplets may fall through the canopy, at angles close to the vertical and impact on the forest floor or small droplets may drift away from the immediate target site, at angles close to horizontal without impacting on the buds and twigs. In the former situation unwanted contamination of the forest floor and understory foliage can take place, whereas with the latter situation, the contamination of an area outside the spray site may result.

Work on Douglas fir and other coniferous foliage in the control of spruce budworm, *Choristoneura occidentalis* (Freeman), established that pine needles most efficiently catch droplets below 50 µm, even at low wind speeds (Himel & Moore 1967, Barry et al. 1977). The mean diameter of such a pine needle is around 1.6 mm. Because maple buds and twigs are larger than pine needles (4-5 mm in diameter), the pine tree studies can only be used as broad indicators of application strategy.

Droplets are collected on plant surfaces by sedimentation and impaction. Smaller droplets (less than 100 µm), because of their near horizontal path in winds greater than 2.5 m/sec (5 mph), are always caught by impaction. Studies on impaction of droplets have shown a complex interaction between the size of the droplet, its relative velocity and the obstacle in its path (May & Clifford 1967). Briefly, the collection efficiency of a target (the percentage of drops caught by a target expressed as a proportion of droplets which could be caught) placed in an airstream increases with droplet size and velocity, and decreases as the target increases with size.

These factors can be brought together in one parameter, the impaction parameter (P). This parameter is a measure of the likelihood of a droplet striking a target assuming it is being transported towards the target with a windspeed V_o.

$$P = \frac{V_s V_o}{gD}$$

V_o = Windspeed
g = Acceleration due to gravity
D = Diameter of target
V_s = Sedimentation velocity of droplet of diameter D

Empirical work has been done to measure catch efficiency (*E*) for various values of the impaction parameter (P) for various shapes of targets by May & Clifford (1967). This work has been recently added to by Spillman & Tongpuy (1987) to take into account variations in turbulence around a target as target size increases. What this means is that if the target dimension and wind speed are known, it is possible to determine what size range of droplets would be able to be caught by the forest canopy.

Of course the airflow inside a canopy is never constant, and the above discussion can only be used as a guideline. Nevertheless, use of such aerodynamic calculations is a good starting point. Table 1 shows calculated droplet sizes which give a high catch efficiency (70%) for different cylinder (twig) diameters at three different wind speeds. It is apparent that even in light winds, small droplets can be caught by twigs. The theoretical data presented in the table would indicate that droplets of 80 - 100 μm would be suitable.

But what about drift? An 80 μm droplet sediments at 16 cm/sec. During the time it takes a droplet to fall from the spray height (typically 15 meters (50 ft) above the canopy) to the top of the forest canopy, one might think it would not have drifted very far. In fact, this is often not the case under commonly occurring weather conditions.

Table 1. Droplet sizes corresponding to capture efficiencies of 70% on different sized cylinders for three different wind speeds

Cylinder diameter (mm)	Windspeed (m/sec)	Minimum drop size (μm)
2.5	1.0	51
2.5	2.5	10
2.5	5.0	7
5.0	1.0	96
5.0	2.5	45
5.0	5.0	10
10.0	1.0	148
10.0	2.5	85
10.0	5.0	56

Droplets sprayed over forests are dispersed by two main mechanisms, sedimentation and turbulent dispersal. Large droplets (greater than 300 μm) have a high sedimentation velocity (V_s), and can be deflected by the turbulent air found within forest canopies. Although moving rapidly, such air behavior would not markedly affect the position of the droplet in relation to its point of release. Smaller droplets have much lower sedimentation velocities, and can be entrained in any turbulent air created by the roughness of the canopy. In other words, the droplet goes where the wind blows. As wind speed increases, the turbulent velocity increases also, and the size of the droplet that is dispersed by the turbulent mechanism (instead of sedimentation) increases. For example, at wind speeds of 1 m/sec, a 100 μm droplet may behave like a large droplet in a forest canopy, essentially reaching the ground through sedimentation. The same droplet dispersed in a 5 m/sec wind however will behave as a small droplet, through entrainment in the turbulent eddies. Such droplet behavior has direct implications on determining which kind of weather conditions should be used for application.

Toxicity of pesticide droplets. The total number of droplets required to provide a high probability that each bud has several toxic doses which would either be ingested or transferred to the insect through physical contact can be broadly estimated. From the previous studies on crops and forests, it is apparent that it is not possible to get an even distribution of droplets on all targets. Instead the pesticide is distributed across a range of targets in a log normal manner, whereby some targets receive no dose or a minute dose, a large proportion receive a small dose, and increasingly smaller groups of targets receive still higher doses (Yendol et al. 1990, Uk & Courshee 1982).

Assuming that the pattern of distribution of droplets on buds and/or twigs is the same as that obtained by Yendol et al. (1990) on foliage, to ensure that 90% of the buds get at least a certain threshold dose, the mean dose rate has to be about five times the threshold value, assuming that the overall catch efficiency of spray is 70%.

In our present example, taking the tree surface area index (the surface area of the trees growing on 1 ha as 1, and 1 liter of spray material evenly atomized into 90 μm droplets (2.62 X 10 drops), this would mean that 90% of the tree area, including buds would get 26.2/5 = 5.2 drops/cm. Admittedly, there are many assumptions and approximations made in this calculation, but accurate models which could be used do not yet exist in forest spray technology. In practice, atomization would be imperfect, resulting in the under production of ideal sized droplets. Application rates would therefore have to be higher than 1 liter/ha to ensure adequate coverage. A further advantage in increasing the application rate and at the same time decreasing the active ingredient concentration would be improved coverage because of the production of greater numbers of droplets. Such lower concentration material would have the added advantage of being less harmful to non-target organisms.

Droplet toxic dose considerations. Because of the very low weight of a pear thrips adult, 25 μg (Foster & Jones 1915), the amount of pesticide in a lethal dose would be very small. Assuming a LC in the range of 10 - 100 ppm, a 90 μm droplet would have between 600 and

60 toxic doses. During the process of bud entry, as well as movement on the bud surface, a thrips would almost certainly receive a toxic dose through ingestion or contact with the pesticide deposit. It has been noted that pear thrips perform considerable exploratory movement on the bud surface before selecting a location for entry into the bud. Therefore, although much of the bud surface might not be covered with pesticide, the acquisition of a lethal dose would still be highly probable if there were some deposits on the bud. An additional increase of pesticide coverage would take place as carbaryl in an oil formulation (Sevin 4-Oil), which would produce a pronounced spread of the insecticide after impaction on a waxy bud surface. These observations must be confirmed experimentally in the laboratory and in field trials before planning a spray program.

The practice in fruit orchards of spraying very high volumes (up to 5000 liters/ha) against thrips ensures that the whole tree is covered with a very low dose of pesticide, and minimizes undosed areas of the bud. Clearly such a strategy is not possible with aerial application.

Atomizer selection. Atomizers used in aerial application fall into two broad categories; rotary, and boom and nozzle. Rotary atomizers enable the droplet size to be controlled independently of the flow rate and spray boom pressure. They therefore have a considerable advantage over conventional nozzle equipment in that adjustments to the droplet spectrum can be made very quickly from the aircraft cockpit during flight with electrically driven units. With such a system the droplet size can be adjusted as required by circumstances. For example, a larger droplet size would be used in a small plot surrounded by sensitive areas to limit potential drift out of the area. A conventional boom and nozzle system would not have this flexibility.

One of the two main types of rotary atomizers used in aerial application is the air-driven Micronair series. Although excellent atomizers for fixed wing work, they would not be suitable on helicopters making short runs; these units require a finite period of time to get up to speed after a turn. Electrically driven Beecomist units, although not capable of handling large flow rates would be the atomizer of choice in helicopters.

Weather considerations. Wind can be used to increase the capture of droplets in the forest canopy. However spraying in a strong wind will result in an overall drift of the swath of spray in a down wind direction. Although, as stated before, under most conditions it will not result in a large long distance drift of off-target spray. Application under such conditions is difficult, however, and can be dangerous because of the turbulence experienced by the aircraft. It is therefore usual to place an upper limit on wind speed of around 5 m/sec (10 mph).

Clear nights during spring in the mountains of New England can produce a strong temperature inversion, where radiational cooling reduces the temperature of the ground and the air immediately in contact with it. Such conditions cause this layer of air to be very stable which tends to dampen down turbulence, whether caused by the wind or by the wake disturbance of an aircraft performing an application. This resistance to allowing mixing of air is potentially dangerous if small droplets (less than 70 μm) are sprayed. Because no turbulent dispersal and impaction occurs, and lateral dispersion is also dampened, such that slowly sedimenting droplets have the potential of drifting long distances out of the target area without much lateral dispersal before they reach the ground. This condition should be watched for, especially if the material to be applied has a potentially serious effect on non-target organisms.

Spatial and temporal dimensions. Given the likely behavior of the adult thrips entering the bud, the spray window open for an aerial application control program appears to be small, lasting over a period of several days. The implications of such a short window would be that the pesticide to be used for control must have a half life which would give it a residual effect 1 to 2 weeks after spraying. This would allow the spray campaign to be performed over a period of about 10 days.

The use of aqueous sprays applied at high volume rates, although still widely used in agricultural aviation, is becoming a rarity in forestry. The work output of spray aircraft is largely inversely proportional to the volume rate being applied. The application of low volume rates therefore enhances the productivity of the aircraft, resulting in the need for a small number of aircraft to perform the control operation. Selection of aircraft and measuring their potential productivity is covered below.

Sugar maple stands in the forests of Vermont are small, typically averaging 4 ha (10 ac) in size. As shown above, a small (80-100 μm) droplet will be the most effective at reaching the selected target (the tree buds). However it would be difficult to confine a spray with such a droplet spectrum within a narrow area. Larger droplets would limit the amount of off-target drift, but would also increase the contamination on the forest floor. Under such conditions a compromise between size and driftability must be made. It is difficult to say exactly how large the Volume Median Diameter (VMD) of the droplet spectrum would have to be; this is an area that should be investigated empirically with field trials. However, based on droplet sedimentation speeds and the excess number of toxic doses in large droplets, it seems unlikely that the droplet VMD should be larger than 150 μm.

Aircraft type. A square area of 4 ha would have dimensions of 200 X 200 meters. A typical single engine agricultural spray aircraft flying at 160 km/h (100 mph) would cover this distance in 4 seconds. A helicopter would be able to fly slower, and more accurately control its application. In addition, at speeds of 80 km/h (50 mph) the helicopter's rotor wash would contribute to the droplet cloud's penetration of the forest canopy. Helicopters also have the advantage of being able to operate closer to the forest areas needing to be sprayed, and not requiring airstrips that may be located some distance away.

Recent Technological Advances In Aerial Application

In recent years technological advances have become available to users involved in aerial application. Two are described here, aircraft characterization equipment and an aerial spray program mission planning computer software package.

The Swath Kit. One of the most difficult jobs in aerial pesticide application for agriculture or forestry is the characterization of aircraft. The Swath Kit was developed for the USDA Forest Service to make weather and deposit measurements on-site and to display results promptly. It allows the user to quickly pinpoint problem deposit patterns and enables quick adjustments to the spray system configuration to be made. The Forest Service recognized a need for such a tool, as existing equipment was not able to quantify spray deposit, nor provide data on droplet spectra.

Before being used operationally, an aircraft needs to be calibrated. However, the aircraft should not be flown until the shape of the deposit pattern beneath the aircraft has been inspected. This second characterization task is a much more difficult problem if more than a visual inspection of the deposit shape is to be made. It is at this stage that the Swath Kit is employed.

The Swath Kit consists of a portable DOS personal computer fitted with proprietary image analysis and weather sensor equipment which is used as a multipurpose data recorder and analyzer. Operationally it can be divided into three parts according to the three broad tasks which comprise the characterization of aircraft.

1) Weather and Information Recording: The weather is monitored during a spray application to ensure suitable conditions exist for the characterization test. The following parameters are measured: wind speed, wind direction, temperature and relative humidity. These are presented graphically on the computer screen to help the user make quick go/no-go judgments on the suitability of the weather.

2) Deposit measurement: After spraying a card-line, the Swath Kit is used in its image analysis mode to measure the deposit on the cards. Deposit is presented in terms of volume of spray per unit area, number of droplets per unit area and percentage of the surface area covered with spray. In addition, size parameters of the droplet spectrum received by each card are presented.

3) Pattern Assessment: Following card measurement, the Swath Kit is used to assess the pattern of the deposit obtained beneath the aircraft. This is done by modelling the swath and presenting visual and statistical data on overlapped swath patterns. Problems in the pattern, such as the presence of peaks or valleys, and assessment of the effective width of the pattern, can be studied at this stage.

CASPR (Computer Assisted Spray Productivity Routine). CASPR was developed and written by the USDA Forest Service Equipment Development Center to automate a method of comparing productivity and costs. This work has been published as a report entitled "A Method for Comparing Cost & Productivity of Aerial Spray Delivery" by Robert Banaugh, Report 84342807, November, 1984. The program is available from Robert Ekblad, at the USDA Forest Service Equipment Development Center, Missoula, Mont.

The computerized method enables "what-if" scenarios to be run for a series of known spray sites. Different aircraft operating from a variety of airports or airstrips can be modelled to maximize productivity and minimize cost. Large airplanes operating from distant airfields can be compared with smaller airplanes operating from nearby airstrips. The cost of using helicopters can be compared with the cost of using fixed wing aircraft. The program is easy to operate, and has context sensitive help available.

Examples of inputs and outputs are presented in Tables 1 and 2 and Figure 1 to demonstrate the rationale of the model. The modelling data are input into worksheets, dealing with application parameters and spray block dimensions, as well as additional ferrying information between spray blocks.

Table 1. Sample information provided by the Computer Assisted Spray Productivity Routine in the data worksheet

Factor	Data/unit	
Application Rate	0.77	liters/acre
Tank Capacity	662	liters
Swath Width	22.5	meters
Spray Speed	185	km/h
Ferry Speed	209	km/h
Turning Time	35	seconds
Auxiliary Ferry Distance	7.2	kilometers
Number Auxiliary Turns	2	
Touchup Constant	0.1	
Spraying Cost Rate	275	$/hour
Ferrying Cost Rate	275	$/hour
Turning Cost Rate	275	$/hour
Touchup Cost Rate	275	$/hour
Loading Cost Rate	0	$/hour
Loading Time/Cycle	7	minutes

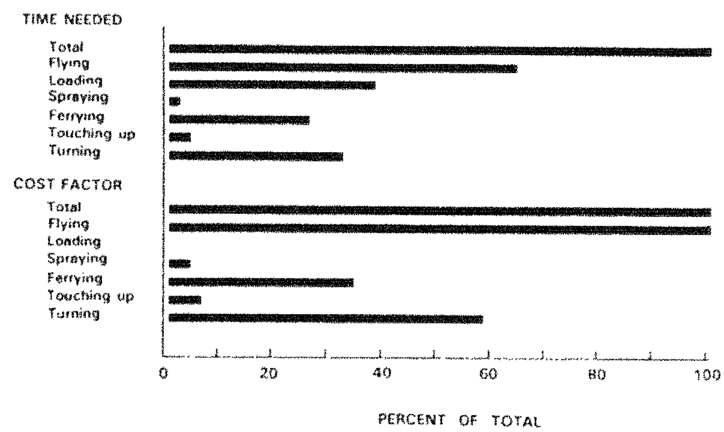

Figure 1. Sample graphic data output provided by the Computer Assisted Spray Productivity Routine from a 0.16 X 0.16 km (0.1^2 mile) block sprayed with a typical single engine fixed wing airplane.

Table 2. Tabular data provided by the Computer Assisted Spray Productivity Routine from a 0.1 X 0.1 mile block sprayed with a typical single engine fixed wing airplane

Factor	Data/unit	
Total Spray Area	2.59	hectares
Material Flow Rate	68.81	liters/min
Spray Cycle Distance	17.70	kilometers
Number of Spray Cycles	1	
Total Spray Distance	1.13	kilometers
Number of Spray Turns	8	
Number of Ferry Turns	2	
Number Auxiliary Turns	2	
Total Number of Turns	12	
Spraying Time	0.35	minutes
Ferrying Time	5.77	minutes
Turning Time	7.00	minutes
Touchup Time	0.74	minutes
Total Flying Time	13.86	minutes

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BIOLOGY AND IMPACT OF *Thrips calcaratus* Uzel IN THE GREAT LAKES REGION

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Introduction

Basswood (*Tilia americana* L.) stands in the Lake States have been experiencing defoliation since around 1979. These symptoms were originally attributed to frost damage because they occur in early spring. However, the pattern of damaged trees was atypical of frost injury. Only basswood trees were affected, and there was no relationship to sites known to be frost pockets. By 1980 it was recognized that a thrips was associated with defoliation. The pest was originally identified as the basswood thrips, *Neohydatothrips* (then *Sericothrips*) *tiliae* (Hood) (Thripidae), a native species. Because this insect has no history of causing damage, the judgement was to let natural forces suppress the population. Outbreaks continued to expand, however, casting doubt on the role of a heretofore innocuous species as the causal agent. Further examination led to the identification of an introduced species, *Thrips calcaratus* Uzel (Thripidae) as the primary pest (Raffa & Hall 1988). This species was first recorded in North America in New York in 1925 (Hood 1927), and is now distributed throughout the Middle Atlantic States, Ontario, and Quebec, in addition to the Lake States.

The outbreak originated in northeastern Wisconsin, near the border with the upper peninsula of Michigan. The progression of infestation and the current outbreak area are shown in Figures 1 and 2. Defoliation shows no signs of abating. Currently, around 81,000 hectares (200,000 acres) are affected each year in Wisconsin (Table 1). There are about 40,470 hectares (100,000 acres) defoliated in Minnesota each year, and additional losses occur in Michigan (Wisconsin Department of Natural Resources 1980 - 1988, Minnesota Department of Natural Resources 1983 - 1987).

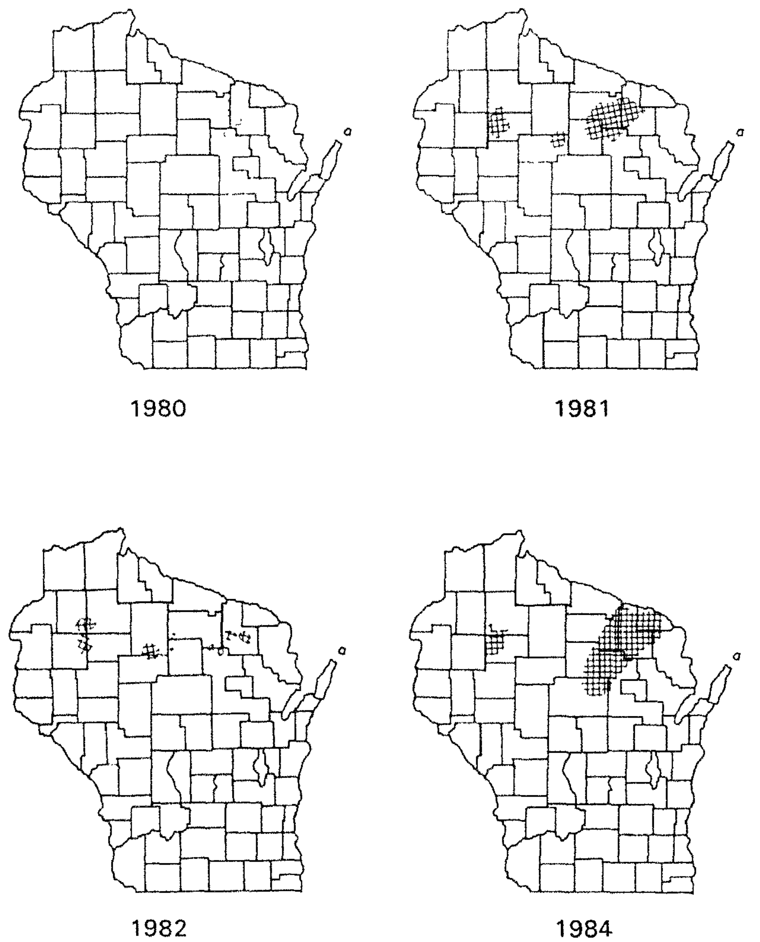

Figure 1. Areas (shaded) of moderate to severe defoliation by basswood thrips in Wisconsin from 1980 - 1984.

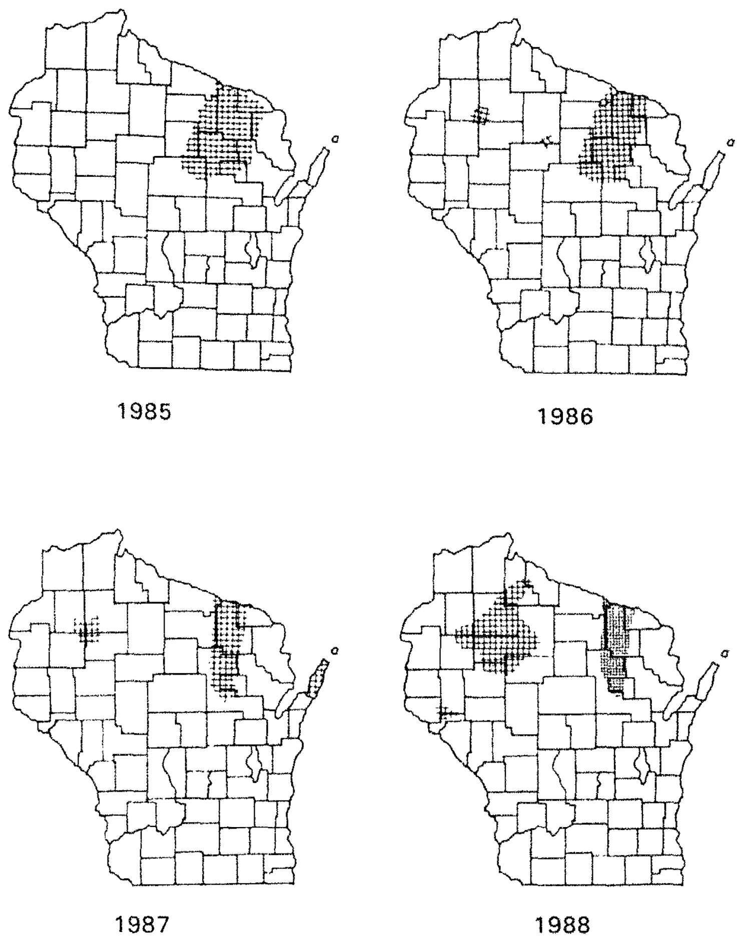

Figure 2. Areas (shaded) of severe defoliation by basswood thrips in Wisconsin from 1985 - 1988. Area shaded with small cross-hatching in the 1988 map represents regions of light to moderate thrips defoliation.

Table 1. Defoliation of *Tilia americana* by *Thrips calcaratus* in Wisconsin from 1980 - 1987[a]

Year	Hectares with moderate to severe defoliation
1980	809
1981	2,307
1982	20,000
1983	40,470
1984	105,222[b]
1985	101,175
1986	101,175
1987	80,940

[a] Data from Forest Pest Conditions in Wisconsin, WI Dep. of Natural Resources.

[b] Includes light defoliation.

Basswood is the third most common tree in the Lake States northern hardwood forest. This region has a large tourism economy, which could be adversely affected by thrips defoliation of this tree species. Basswood also has important commercial uses such as veneer, furniture, and particle board. This tree is also an important soil-improvement and wildlife habitat species (Fowells 1965, Panshin & de Zeeuw 1980, Beier 1985).

Basswood Thrips Bioecology

Very little is known about *T. calcaratus* biology. Because this species is not a pest in its native European range, it has not been studied beyond the taxonomic level (Gentile & Bailey 1968, Jacot-Guillarmod 1975). It has been recorded on nine tree genera, including some which occur in association with basswood in the North American range of *T. calcaratus*. The latter include maple, hickory, beech, ash, and oak. However, there are no rearing data available, and so these may be just casual associations. The European data suggest that *Tilia* species are the only suitable breeding hosts (Jacot-Guillarmod 1975). The European hosts are *Tilia europa*, *T. platyphyllos*, and *T. vulgarus*. There are no data on developmental rates, fecundity, or behavior. The species is believed to consist entirely of females, as no males have been collected.

Thrips calcaratus appears to tolerate a wide range of climatic conditions. It is distributed throughout almost all of Europe, north to Denmark, south to Italy, west to Great Britain, and east to the Ukraine (Jacot-Guillarmod 1975). Thus, it seems that this species will ultimately colonize the entire range of basswood in North America.

In 1988 we initiated a two-year study on the life history and impact of *T. calcaratus*. Twelve permanent 0.10 hectare (0.25 acre) plots were established in April. Thirty basswood trees were randomly selected per plot. Tree data on each tree, including defoliation estimates in 1988 and 1989 and increment cores in 1989 were taken at scheduled times. Insect data were collected on eight plots, and include collections from two emergence traps and six soil/litter samples per plot per week. Soil samples were extracted using Berlese funnels. Direct observations of thrips adults and larvae in the field were also made.

T. calcaratus overwinters in the soil as an adult. Emergence begins during the first week of May in southern Wisconsin, and about a week later in the northern counties. Emergence is highly synchronous, being nearly complete by the end of the second week of May in the south, and late May in the north. Adult emergence coincides with basswood bud swelling. They feed in the opening buds, just as the leaves are starting to expand. The opening leaves show a shotgun effect, in which small feeding holes shred and further tissue degradation occurs. The leaves become chlorotic, and eventually drop off if feeding is extensive. Oviposition appears to occur in the main veins of the lower leaf surface. Larvae appear in early June, by which time very few adults can be found. Because a high degree of defoliation has already occurred by this time, adult feeding is probably the main source of injury. Larvae complete development in June, drop to the ground, and burrow into the soil. Soil populations are much higher than litter populations. Development to the adult stage for most *T. calcaratus* is complete by mid-July, although some immatures are present into September. There is one generation per year.

Impact of Basswood Thrips

The impact of thrips feeding on basswood trees is largely unknown. We subsampled 77 trees in 1988, and based on these preliminary data, defoliation above 30% appears to reduce radial growth (Table 2). Branch dieback has also been observed. Defoliated trees do refoliate, but the new leaves appear small, chlorotic, and sometimes scorched at the edges. The actual source of injury remains a mystery. The amount of damage surely exceeds the actual consumption rates by these tiny insects. Feeding appears to induce necrosis around the site of puncture, but whether this is due entirely to mechanical damage is unknown. The chlorosis suggests that phytotoxic secretions may be involved, but we have no evidence for this.

Table 2. Effect of defoliation by *Thrips calcaratus* on radial growth of *Tilia americana* in northwestern Wisconsin in 1988

Defoliation (%)	*n*	Annual Radial Growth (% Increase)
0 - 30	10	0.81
40 - 60	20	0.49
70 - 100	47	0.42

Before we can develop intelligent management strategies, we need to answer some very basic questions about why this insect is so damaging here, but so innocuous in Europe. At least two biological features need to be considered. The first is natural enemies. Whenever an introduced species undergoes outbreak behavior in its new zone, the possibility of escape from predators, parasites, and pathogens that regulate population densities in the native range must be considered. This may provide an opportunity for classical biological control through the introduction of natural enemies from Europe. In addition, the North American natural enemy complex should be characterized so that any control strategies against *T. calcaratus* do not negatively impact beneficial species.

A second consideration is that American basswood may be more sensitive to *T. calcaratus* feeding than European *Tilia* species. In Wisconsin, thrips injury has not been observed on ornamental linden, which is almost entirely of European stock. For example, 60% of ornamental *Tilia* are of the Greenspier cultivar, derived from European littleleaf linden, *T. cordata*, and in the Lake States most of the remainder are Redmond linden, a cross of the European *T. euchlora* with *T. americana*. Perhaps these species can support thrips populations, but are either less favorable for development or more tolerant to thrips feeding. However, an alternate explanation of why ornamental trees have not suffered damage is that site conditions may be unsuitable. Native basswood stands normally occur on relatively rich soils, with thick litter layers, certainly different conditions from most lawn trees. The host range, both of suspected suitable genera and other potential hosts within *Tilia* needs to be critically examined.

Acknowledgment

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Discussion Period

Question: Do you think the black plastic on your emergence cage effects your results? Do you have any data that suggests a change in soil temperature that might alter thrips phenology?

Raffa: Probably the black plastic warms up the soil to a certain amount. Our goal this spring was to get an indication about when to concentrate our research efforts. We now know there is about a 3-week period when they emerge. In the future, we are going to try different sampling methods within that time.

Question: You mentioned that thrips damage could result in growth loss. Have you had any examples of mortality or subsequent decline in those trees?

Raffa: The only examples we have of mortality has been landowner testimony. Based on these sources there does appear to be some mortality due to thrips damage. However, we have no direct evidence of this. I don't expect mortality to be very high considering the amount of damage that has occurred.

Question: Have you done any work on chemical control for basswood thrips?

Raffa: No control methods have yet been tried. At this point we wouldn't know how to go about doing it. There are also economic issues to consider. I have described to you the virtues of basswood, but not everybody would agree with me. The softwood industry predominates in the Lake States and many people do not consider the basswood to be of high value. In our state the Mongamy Indians are the principle hardwood managers and the impact of basswood thrips damage will probably be greatest on them. However, we don't have good data on the economic value of this tree.

Question: You mentioned that you plan to look at the predacious insects that attack basswood thrips. Have you found promising predators?

Raffa: No, not yet. All our specimens are in vials. We have finished the extractions and have separated the thrips, but the rest must still be analyzed. It is a very important question though. I disagree with the Governor, who said yesterday that it is better to act and make a mistake than to do nothing at all. Certainly our history and biological experience doesn't support that. It is critical to know how our control strategies may effect beneficial organisms and the overall environmental balance before they are implemented.

Question: Once you identify the predators in your samples, how are you going to make associations with basswood thrips?

Raffa: We're not. That would require elaborate biological studies. Our work on basswood thrips is a boot-leg effort; we have no formal research program in this area so any work on predators will have to be on a small scale.

Question: What do the thrips do in the ground?

Raffa: I think they are in an overwintering stage by that time, based on the population profiles we've seen in the emergence data and the soil data. We've found adults in the soil from early June to early July, and prior to that only larvae in the soil and after that no larvae in the soil. One thing we wondered about was could basswood thrips have alternate hosts that support it but don't show the same level of sensitivity to feeding. It is possible that there is an allergic reaction or something like that in basswood.

WESTERN FLOWER THRIPS, A SERIOUS PEST OF FLORICULTURAL CROPS

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The western flower thrips, *Frankliniella occidentalis* (Pergande), has recently become one of the most serious pest problems facing the ornamental industry (Robb & Parrella 1988). It is polyphagous and has been collected from plants of almost every order of the Spermatophyta in California (Watson 1923, Bailey 1933, Bryan & Smith 1956). However, western flower thrips probably has a greater impact on ornamental crops than any other crop. It attacks essentially all floricultural crops and also transmits the tomato spotted wilt virus to numerous ornamental plants (Best 1968).

Tomato spotted wilt virus, like western flower thrips, has a very broad host range, which includes numerous field crops, vegetables, weeds and ornamental crops (Best 1968). Tomato spotted wilt virus is only transmitted by a few thrips species; no other vectors have been identified. Western flower thrips is one species known to vector this virus and it is currently the primary vector associated with this disease in United States; on the East Coast (Da Graca et al. 1985), in the southern states (Barnes & Halliwell 1985, Greenhough et al. 1985), the western states and Hawaii (Allen et. al. 1983, Cho et al. 1987, Robb et al. 1988), as well as in Canada (Allen & Broadbent 1986, Broadbent et al. 1987).

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Damage thresholds for floricultural crops are very low or non-existent. This is especially true for pests such as the western flower thrips which attack the flower, the most important part of these aesthetic crops (Parrella & Jones 1987). Flower losses caused by thrips damage, because of reduced crop yields and market values, as well as increased costs for additional pesticide applications, have been staggering for many ornamental crop producers (Robb & Parrella 1988). Despite its broad host range, vector capabilities and the economic importance of this pest, there have been surprisingly few studies on its biology.

Development of Western Flower Thrips

Although this insect is occasionally found on the foliage of some plants, it is primarily anthophilous. Eggs are deposited within plant tissue and first instars begin feeding upon egg eclosion. Second instars are also active feeders. Both larval instars are thigmotactic and are generally found in the protection of the perianth of the flower or within developing terminal foliage. Second instars become whitish in color just prior to the next molt and usually move down the plant to pupate in the soil or plant litter. Prepupae and pupae are quiescent non-feeding stages whereas the adult resumes feeding. Females are larger than males and can vary in coloration from yellow to dark brown while males are always pale yellow. Females arise only from fertilized eggs, but they are facultatively arrhenotokous and can produce male offspring from unfertilized eggs.

Under field conditions in California, Bailey (1933) reported a life cycle length of 15-20 days for the western flower thrips. Bryan & Smith (1956) determined the developmental times of western flower thrips at 15°, 20°, and 26.7°C on wild radish leaves and Lublinkhof & Foster (1977) evaluated development times and fecundity at 15°, 20° and 30°C on green bean sections. However, since there had been no evaluations of western flower thrips development on an ornamental crop, a trial was conducted to determine their development on the ornamental host, chrysanthemum, at selected constant temperatures.

Western flower thrips were confined to chrysanthemum, cv. Hurricane, leaves using a modified Munger cell design (Munger 1942, Morse et al. 1986, Robb 1989). Pollen was provided to the thrips. Leaf petioles were suspended in water, and the leaves were changed at least every three days.

Adult female thrips were exposed to chrysanthemum leaves for oviposition for four hours at a constant temperature of 25°C. The adults were removed and the leaves were held in temperature cabinets at 15°, 20°, 25°, 27.2°, 30° or 35°C. The development of each thrips was monitored every four hours until it became an adult.

The highest rate for total development from egg to adult was 30°C (Table 1). Plotting the development rates against temperature revealed a sigmoidal curve. The development rates determined by this experiment were fit by the biophysical model of Wagner et al. (1984) (Fig. 1). A four-parameter model, with high temperature inhibition, best fit the developmental data with 50% high temperature inhibition at 33.26°C.

Table 1. Egg to adult development times of *Frankliniella occidentalis* (Pergande) at selected constant temperatures

Temperature Regime (°C)	*n*[a]	Mean hours	(±SE)	Development Rate ($Time^{-1}$)
15	44	939.16	(14.191)	0.001065
20	33	625.85	(20.436)	0.001598
25	51	309.95	(9.161)	0.003226
27.2	25	245.57	(4.275)	0.004035
30	36	223.33	(4.444)	0.004478
35	33	257.79	(5.183)	0.003879

[a] Total number of individuals evaluated, trials replicated at least three times for each temperature regime.

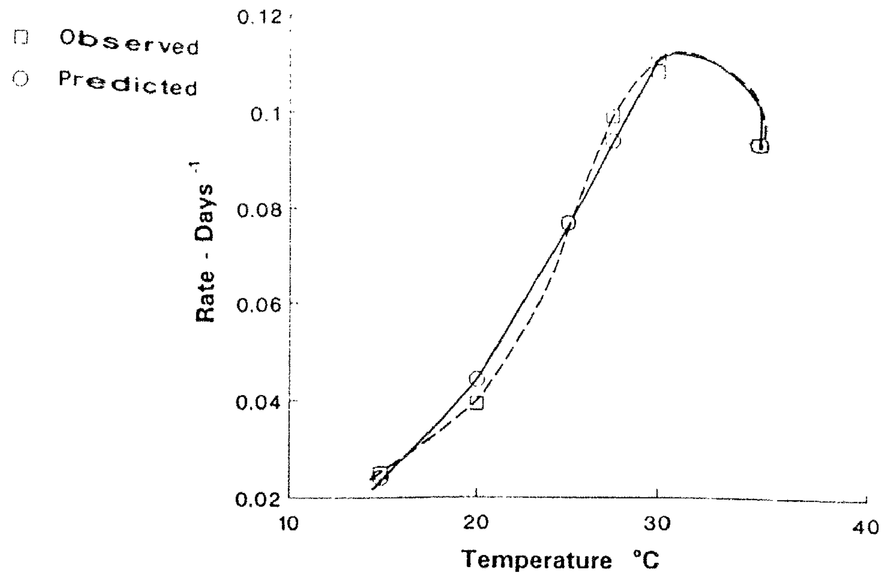

Figure 1. Development rates of *Frankliniella occidentalis* (Pergande) at selected temperatures and nonlinear regression fit by biophysical model.

The development rates observed in this study differ from those reported by Bryan & Smith (1956) on wild radish and by Lublinkhof & Foster (1977) on green bean sections. These differences probably reflect responses of this thrips species to the different host plants utilized in each trial. Dintenfass et al. (1987) observed an exponential increase in western flower thrips populations in onion fields up to temperatures of 35°C whereas above 35°C, development was considerably reduced. Their results were based on ambient field temperatures, however the temperature in the microenvironment of the thrips was probably lower, being modified by the crop canopy. Thus, the results of Dintenfass et al. (1987) generally agree with the findings of this study.

Longevity and Fecundity of Adult Female Western Flower Thrips

Adult male and female pairs were confined to chrysanthemum leaves at the temperature regimes described previously. Adult mortality was assessed daily to determine age specific survival (l_x). Leaves were changed every other day and subsequently held for seven days at 25°C to ensure emergence of all larvae. Emerging larvae were transferred to fresh leaves and maintained until adult emergence to determine sex ratio and age specific fecundity (m_x). The l_x and m_x data were used to compile life tables for each temperature regime (Carey 1982).

The greatest numbers of progeny per female and progeny per female per day were produced at 27.2°C (Table 2). In addition, mean longevity of females maintained at 27.2°C was almost three times as long as the mean longevity of females at 30°C. Net reproductive rate, R_o, was greatest at 27.2°C and dropped sharply as temperature increased. Intrinsic rate of increase, r_m, was lowest at the temperature extremes and mean generation time decreased with increasing temperature. It is clear from this short generation time and high reproductive rate how quickly large populations of western flower thrips can build up in greenhouses. Other factors, such as migration, also influence the numbers of thrips in greenhouses.

Western Flower Thrips Movement Into and Within Greenhouses

Numerous crops and weeds serve as hosts of western flower thrips outside greenhouses. Adults, after their original host plants senesce or are harvested, search for and move to new hosts. Adult dispersal is initiated with the adults launching themselves into the wind (Lewis 1973). Thrips are not strong fliers, and airspeed is negligible in relation to the speeds of circulating winds (Johnson 1969). Even in relatively calm weather, wind speed is greater than thrips' flight speed (Lewis 1973). Consequently, thrips can be dispersed great distances and can be carried into greenhouses through openings such as open doors and vents.

Table 2. Longevity, fertility and life table parameters of *Frankliniella occidentalis* (Pergande) at selected temperatures

Temperature Regime (°C)	n^a	Longevity Days	(±SE)	Mean No. Progeny/ Female	(±SE)	R_0^b	r_m^c	T (days)	t_2 (days)
15	9	46.33	(9.735)	50.51	(18.771)	42.25	0.0563	66.523	12.311
20	9	75.17	(10.131)	125.88	(34.676)	86.49	0.0941	47.186	7.366
25	10	31.40	(3.776)	135.60	(46.550)	99.51	0.1713	26.856	4.046
27.2	9	34.00	(4.120)	228.60	(34.502)	124.92	0.2545	18.969	2.724
30	11	12.67	(2.833)	42.00	(14.292)	35.39	0.2054	17.366	3.381
35	10	9.50	(2.604)	5.10	(3.567)	2.69	0.0563	17.565	12.312

[a] Total number of individuals evaluated, trials replicated at least three times for each temperature regime.

[b] Net reproductive rate.

[c] Intrinsic rate of increase.

Colored sticky traps were used to evaluate thrips movement within greenhouses. Yellow sticky traps are attractive to many pests of ornamental crops, including whiteflies, aphids and leafminers (Roach & Agee 1972, Parrella & Jones 1985, Jones & Parrella 1986). White and blue traps have been reported to be as attractive, or more, to western flower thrips than to other common ornamental pests (Moffitt 1964, Beavers et al. 1971, Yudin et al. 1987, Brødsgaard 1989).

The attractancy of white, yellow, blue and green traps to western flower thrips was determined in a chrysanthemum greenhouse. Colored acrylic panels (12.8 X 17.8 cm) were used for traps. The panels were placed inside a polyacetate envelope which was covered with a very thin layer of Tanglefoot®, which traps insects as they alight without affecting the attractancy of the trap (Prokopy 1968, Gregory 1985). Traps were suspended over benches of chrysanthemums. Four traps, one of each color, were placed over four benches in a Latin square design. The traps were left in place for 48 hours and then the thrips were counted. Traps were rearranged and the trial was repeated four times. Data were analyzed using analysis of variance procedures. Treatment means were separated using Duncan's multiple range test.

Blue and yellow were the most attractive colors to western flower thrips (Table 3). Yellow traps were chosen for all subsequent trials since yellow is attractive to other pests of ornamental crops (Roach & Agee 1972, Parrella & Jones 1985, Jones & Parrella 1986).

Evaluations in rose, carnation, chrysanthemum and poinsettia greenhouses indicated that several factors affected western flower thrips movement. These factors include movement into greenhouses, crop type and cultivar composition. Mark-recapture studies demonstrated that adult thrips were trapped at greater distances from the release point in greenhouses containing poinsettias, a non-preferred host, than in greenhouses with roses, a preferred host. In the rose greenhouse, 72.2% of the thrips were recaptured within 20 m of the release point. No thrips were captured near the release point in the poinsettia greenhouse and more than half were caught 96 m from the release point (Robb 1989).

Table 3. Effects of trap colors on attractancy to *Frankliniella occidentalis* (Pergande)

Trap Color	*n*[a]	Mean No. (±SE) thrips/trap[b]
Green	16	40.00 (5.038)a
White	16	86.88 (10.396)b
Yellow	16	125.50 (14.609)c
Blue	16	150.50 (19.519)c

[a] Total number of traps evaluated per color. Traps were changed and rearranged every 48 hours. Trial was replicated four times.

[b] Means followed by the same letter do not differ significantly ($P > 0.05$) Duncan's multiple range test.

Significant differences were also observed in the attractancy of different cultivars of carnations and roses to western flower thrips. The spectral reflectance of different cultivars probably accounted for some of the differences observed with cultivar composition (Robb 1989). Other factors are also important, however. In roses, for example, flower development and time of sepal splitting also affected the number of thrips in the flowers. Early splitting cultivars had a longer exposure time to adult females and a greater percentage of larvae were present at harvest (Robb 1989). It is clear from these results that an understanding thrips biology and behavior is crucial to the development of integrated control strategies for this pest.

Western Flower Thrips Control Strategies

Chemical control of western flower thrips can be extremely difficult for many reasons. Good contact of thrips with pesticides is hard to achieve due to the thigmotactic behavior of this insect. Its propensity to develop insecticide resistance is another factor which complicates control. Reinfesting populations through migration of thrips into greenhouses further complicates the problem.

Based on our knowledge of the biology and behavior of this pest, several management strategies have been developed. An integrated approach incorporates strategies for the reduction/prevention of western flower thrips in the greenhouse, without relying solely on insecticides for control. While all these strategies may not be appropriate for every situation, many can be used by almost every grower.

Physical Controls

Thrips exclusion. The most effective strategy for thrips control is prevention (Robb 1990). Many greenhouse structures have open sides or vents for increased ventilation. However, this offers no impediment to thrips movement into these greenhouses. Therefore, screening over vents and doorways can greatly reduce this movement into greenhouses and reduce or eliminate the need for insecticides.

Isolation of propagation areas. One of the most important factors in managing thrips populations is to start with clean plant material. However, this is virtually impossible if thrips move from production areas to stock and rooting areas.

Therefore, isolation of stock and propagation areas is crucial. Physical barriers, such as screening or distance from production areas can serve to isolate propagation areas.

Cultural Controls

Weed control around greenhouse. As mentioned previously, western flower thrips have a broad host range, including weeds as well as flowering plants. Weeds, however, are not usually targeted for pesticide applications and can serve as a refuge during pesticide applications. Moreover, weeds can act as a reservoir for tomato spotted wilt virus.

Avoidance of continuous cropping. Many flower crops are grown in very large, contiguous greenhouses. All stages of production may be present under one roof. As crops are harvested, mobile adult populations can move from an older planting to a newly planted area. Thus, a constant food supply is available to the thrips and populations will continue to flourish. Whenever possible, large growing areas should be broken into smaller units to reduce this problem.

Disposal of plant residues. Once a crop has been harvested, it is a good practice to get rid of the plant residues immediately. Like weeds, these plants have no commercial value, but are still capable of supporting large populations of thrips which may move onto younger plants. This situation can be avoided simply by removing plant residues.

Monitoring of thrips population levels. Greenhouse conditions are suitable for *F. occidentalis* development throughout the year, including winter. Once established in a greenhouse, control may be difficult to obtain, so early detection is important. The fact that viruliferous adult *F. occidentalis* can transmit tomato spotted wilt virus to healthy plants in a period as short as 30 minutes makes early detection of this insect even more imperative (Sakimura 1962a, 1962b). Thus, knowledge of *F. occidentalis* movement into and within greenhouse is crucial to the utilization of integrated pest management strategies.

In all trials, the use of yellow sticky traps provided a good assessment of *F. occidentalis* populations and was faster and easier than sampling the flowers. Moreover, the sticky traps afforded early detection of *F. occidentalis* permitting remedial action before populations reached damaging levels. Analysis of the mean and variance data from numerous monitoring trials indicated that an average of five traps per hectare was sufficient to estimate *F. occidentalis* populations in greenhouses (Robb 1989).

Chemical Control

When monitoring indicates that chemical control is necessary, certain strategies help to maximize the efficacy of the treatment.
Two applications made five days apart are recommended to reduce high populations of western flower thrips because chemical controls are

not effective against eggs and sprays are not usually directed against the pupae in the soil. Good coverage and penetration into the dense flowers, buds and terminal foliage is essential and is enhanced with smaller droplet sizes.

The development of insecticide resistance is a serious concern with western flower thrips control (Robb 1989). Therefore, it is important to rotate classes of insecticides. A rotation of classes every 4-6 weeks, based on two-three generation times of western flower thrips at greenhouse temperatures has been suggested.

There is no single best solution for dealing with the problems of insecticide resistance; the best approach is the integration of various management strategies, including cultural, physical and biological control alternatives. An integrated approach alleviates the constant insecticide pressure on *F. occidentalis* and helps retard the development of insecticide resistance.

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THRIPS ON STONE FRUITS: FORMATIVE STAGE OF PEST MANAGEMENT

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Abstract

Thrips populations and injury attributed to their feeding on nectarine and peach fruit surfaces were monitored in sprayed and unsprayed orchards in central Georgia from 1983-1988. *Frankliniella tritici* (Fitch), the eastern flower thrips; *F. occidentalis* (Pergande), the western flower thrips; and *Neohydatothrips* (= *Sericothrips*) *variabilis* (Beach), the soybean thrips; were the most abundant of the 31 thrips species recovered from the orchards. Their relative abundance changed each year. The western flower thrips appears to be most damaging in causing russeting on nectarine surfaces. Silvering injury to peaches and nectarines was caused by either or both of the flower thrips and coincided with peak populations of adults at or near final fruit swell on early ripening cultivars. Soybean thrips caused little or no injury to fruit. None of the above mentioned flower thrips species were recovered from various weed and grass species in and near the nectarine orchard during two years of overwintering studies. Control strategies are based on sampling for thrips adults and larvae.

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Introduction

Peaches are a valued fresh fruit crop in the southeastern United States. Georgia and South Carolina produced and shipped 217.4 million kg (480 million pounds) with a gross value in excess of $80.1 million in 1988 (Ga. Agric. State Service 1989).

Although peaches are by far the major stone fruit in the Southeast, nectarines appear to have potential for future markets in this area. Recently there has been new interest in developing nectarine cultivars adapted to the Southeast (Okie et al. 1985). Insect control strategies for peaches have been relatively static for several years with no major emphasis on thrips control, simply because thrips injury has been a minor problem. However, this strategy may change due to the recent introduction of the western flower thrips, *Frankliniella occidentalis* (Pergande). At present, we have no spray guide specifically for nectarines. Comments are made in the peach spray guide advising those growers (limited number) who produce nectarines as to modifications in the peach pest practices which are necessary or appropriate for nectarines (Bertrand et al. 1988). Reports from California have noted that thrips injury due to *F. occidentalis* is a problem in certain California nectarine producing areas (LaRue et al. 1972) and to a lesser degree on peaches (Weldon 1921). Indications are that southeastern nectarine producers will face similar problems.

Thrips Threat to Nectarines and Peaches

In 1980, the western flower thrips was first reported to be damaging cotton in the Southeast and in 1981 it was reported as a new pest on peanuts in Georgia (Beshear 1983). Also, the species has been shown to be a vector of tomato spotted wilt virus on tomatoes and peanuts (McRitchie 1986, Hagan et al. 1987). Until 1983, very little information was available on thrips and their association with peaches and nectarines in the Southeast. During 1983 and 1984, we regularly surveyed for thrips in non-sprayed peaches and sporadically sampled in sprayed peach orchards in 1984 and 1986. In 1986-88 we concentrated on non-sprayed nectarines in order to gather basic life history data on damaging thrips species (Yonce et al. 1988). In 1988 we further expanded our studies to sprayed peaches (Horton et al. 1988). We needed to determine which thrips species were important, their seasonal distribution patterns, and if the western flower thrips was becoming established on nectarines and peaches in the Southeast.

Thrips Sampling Procedure

Sampling was done with a modification of a unique sampling device designed and originally built for sampling pecan arthropods (Tedders 1983). Two aluminum trays (117 x 76 cm) were placed under the canopy of a tree designated for sampling, and the limbs above were then sprayed with a short residue, knockdown insecticide (6% pyrethrin plus 60% piperonyl butoxide). Application was made with a small battery powered Porta-Jet® sprayer (Fig. 1). After 30 min. trays were picked up and placed on a supporting framework, and arthropods were washed with water into a trough through a funnel into sheer cloth bags after which they were removed and placed in 70% ethanol. Thrips were later separated and identified by methods described by Allen & Broadbent (1986), Sakimura (1986), Stannard (1968) and Moulton (1948). Voucher specimens were sent to S. Nakahara (USDA-Insect Identification Lab., Beltsville, Md. 20705) for verification. Sampling was begun at bud swell and continued at weekly intervals until harvest, then every two weeks until 1 September.

Fruit Injury Damage Types

There are two types of injury to fruit. Russeting is a rough textured, tan-colored blemish that may result in cullage (Fig. 2). At bloom time, adult flower thrips enter the flower and lay eggs in tender flower parts near the ovary. Subsequently, eggs hatch and the young larvae remain inside the flower. Oviposition wounds and feeding by small larvae on the young embryonic fruit produce injury that is greatly magnified on the mature fruit at harvest time. The appearance is often referred to as "buckskin." Silvering, the other type of injury, is less severe and results in a benign, light-colored blemish (Fig. 3). It seldom produces cullage of fruit in the commercial market. It is caused by adult and immature thrips feeding on outer layers of pigment-containing cells and results in bleaching and speckling of the red blush when fruit begins final swell. Silvering seems to be more common on cultivars that ripen when adult flower thrips populations are peaking.

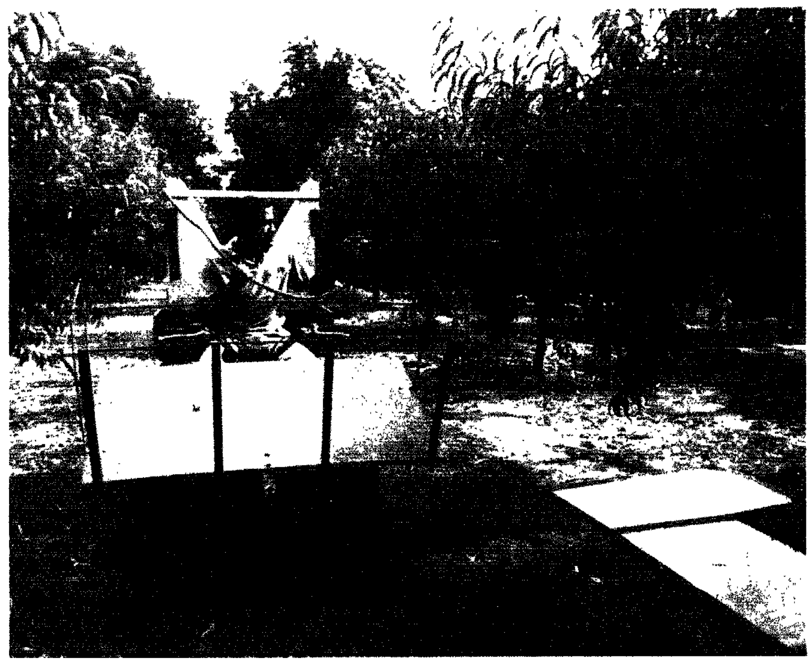

Figure 1. Handgun application of pyrethrin-piperonyl butoxide insecticide mix to sample thrips populations in peaches. Thrips are collected in white trays placed on the ground.

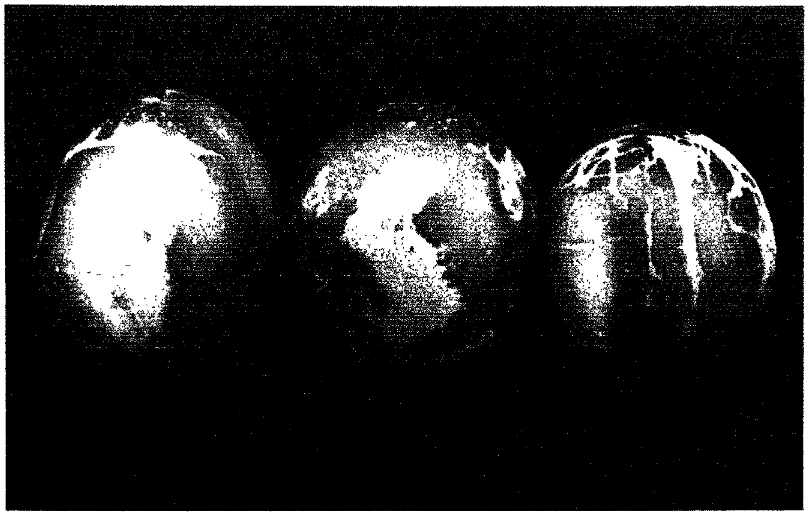

Figure 2. Nectarines with moderate and severe russeting from thrips feeding.

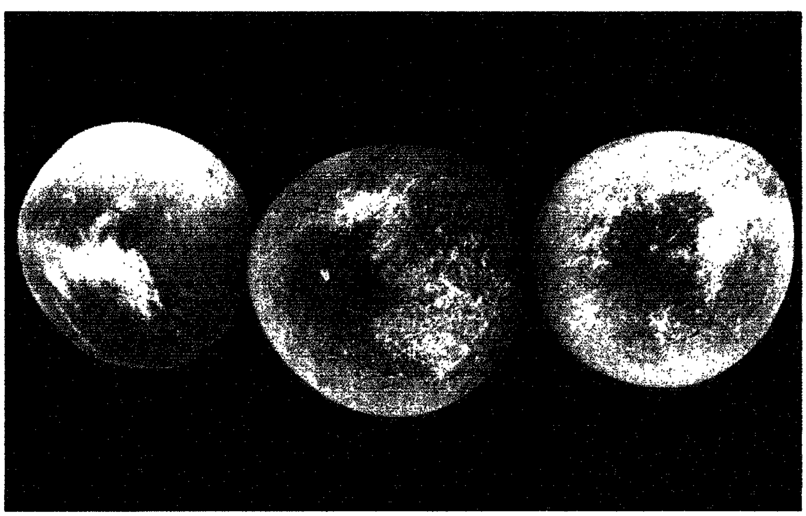

Figure 3. Peaches with light and moderate silvering injury from thrips feeding.

Results and Discussion

Orchard Experiments

In 1983 and 1984, our sampling in non-sprayed peach orchards at Byron, Ga. revealed the presence of 31 species of thrips (Table 1). The majority of captures were the eastern flower thrips, *Frankliniella tritici* and the soybean thrips, *Neohydatothrips* (= *Sericothrips*) *variabilis*. Captures of other species were much less common; half of the species were incidentals and a few were captured only once or twice during the entire two-year period.

Limited sampling was done concurrently in commercial sprayed peach orchards in 1984. Thrips captures in these orchards were not different from captures in non-sprayed orchards. This was the first circumstantial evidence that thrips populations were virtually unaffected by standard insecticidal control strategies that rely almost exclusively on ethyl parathion. During a three-year study (1986-88) of intense sampling for thrips in non-sprayed nectarine plantings, the western flower thrips, *F. occidentalis*, became noticeably more abundant. In 1986 western flower thrips were considerably more common than they had been in the two previous years' sampling in peaches. In 1987 this trend reversed; western flower thrips was almost nonexistent, the eastern flower thrips, *F. tritici*, captures were very few, while the soybean thrips were quite prevalent. Conversely, in 1988 the western flower thrips were more abundant than all the other species.

Sampling in commercial peach orchards during 1988 revealed a high incidence of silvering on some peach cultivars that ripened during the time when western flower thrips populations were peaking. However, the soybean thrips appeared to contribute very little to russeting or silvering injury. Damage to fruit was low during 1987 when the soybean thrips population was dominant over flower thrips. In one experiment, the number of soybean thrips recovered from nectarine trees without fruit was equal to the number of soybean thrips recovered from trees with fruit. This was further evidence confirming that soybean thrips are unimportant in causing fruit injury to nectarines.

Table 1. Thrips species captured in unsprayed "Redskin" and "Redglobe" peach orchards in 1983 and 1984. USDA Fruit and Tree Nut Research Laboratory, Byron, Ga.

SUBORDER TEREBRANTIA	
Aeolothipidae Uzel (1895)	**Heterothripidae** Bagnall (1912)
Aeolthrips bicolor Hinds	*Heterothrips quercicola* Crawford, J.C.
Aeolothrips melaleucus Haliday	
Thripidae Stephens (1829)	
Breqmatothrips qracilis Hood & Williams	*Microcephalothrips abdominalis* (Crawford, D. L.)
Breqmatothrips venustus Hood	*Neohydatothrips variabilis* (Beach)
Caliothrips nr. phaseoli (Hood)	*Plesiothrips perplexus* (Beach)
Chirothrips mexicanus Crawford, D. L.	*Pseudothrips inequalis* (Beach)
Frankliniella bispinosa (Morgan)	*Salpingothrips aimotofus* Kudo
Frankliniella fusca (Hinds)	*Scolothrips pallidus* (Beach)
Frankliniella occidentalis (Pergande)	*Sericothris cinqulatus* Hinds
Frankliniella tritici (Fitch)	*Thrips hawaiiensis* (Morgan)
Limothrips cerealium (Haliday)	*Thrips trehernei* Priesner
SUBORDER TUBULIFERA	
Phaeothripidae Uzel (1895)	
Elaphrothrips armatus (Hood)	*Hoplandrothrips japonicus* Karny
Elaphrothrips coniferarum (Pergande)	*Leptothrips mali* (Fitch)
Haplothrips (K.) *graminis* Hood	*Megalothrips spinosus* Hood
Haplothrips (K.) *harti* (Hood)	*Neurothrips magnafemoralis* (Hinds)
Hoplandrothrips microps Hood	*Plectothrips antennatus* Hood

Control Status

At present, our efforts to control thrips injury on nectarines and peaches in the Southeast are less than satisfactory, particularly with respect to russeting injury on nectarines. Although we have managed to suppress russeting in some of our control experiments, it appears that timing of insecticide applications is most important. There is also a need to screen chemicals to find something better than those presently recommended. Early season migration of flower thrips into the orchards needs to be studied more thoroughly. Possibly, pre-bloom spraying or some type of orchard management to destroy overwintering hosts might intercept or disrupt thrips movement into the flowers before they oviposit. Silvering, on the other hand, can be controlled more easily with chemicals since we now have predictable seasonal distribution patterns that allow us to look for thrips and injury on cultivars that ripen when our flower thrips populations peak (15 May-1 June).

Pest Management

Thrips pest management in southeastern stone fruits is, as our title implies, in infancy. The recently established presence of western flower thrips seems to have heightened the pest potential of this group. Nectarines and probably plums are more at risk for thrips injury than peaches.

We lack adequate early season sampling techniques that might help in timing insecticide applications. Berlese funnels are currently in use to refine our knowledge of when flower thrips move to stone fruit to lay eggs and feed. Detailed chemical exclusion studies aimed at refining our excessively broad early-season control windows are to be conducted this season. White sticky traps may be used after more detailed information on thrips movement into orchards is obtained. Preliminary trials with white traps were discouraging, as heavy early-season orchard traffic tends to litter the traps with debris and limit their usefulness. Current recommendations for nectarines suggest preventive application of formetanate hydrochloride (Carzol) at pink bud and petal fall. This is a provisional recommendation based on materials and timing recommended in California, France, Italy, and Greece (Rice, personal communication, University of California; Bournier 1973; Cravedi et al. 1983; Kourmadas et al. 1982; Cravedi & Molinari 1984). Further refinements are obviously needed in these russet prevention sprays. Silvering as previously noted is much less damaging. Current recommendations simply require careful observation. Spraying may be necessary if abundant thrips and/or injury are detected during final fruit swell. Correlation of thrips numbers to injury in susceptible cultivars is a future research goal.

Summary

After 5 years of seasonal thrips sampling in both peach and nectarine orchards, the following points are noteworthy:

1. The western flower thrips is well established in central Georgia and appears to be more damaging to fruit than the eastern flower thrips.

2. Russeting injury occurs very early in fruit development and could require an insecticide as early as pink bud. Lack of sampling techniques prevents spraying as needed. We hope to narrow the treatment window as our knowledge of thrips biology on southeastern stone fruit improves.

3. Silvering occurs near final swell of fruit when peaches and nectarines begin to show a substantial amount of red blush before ripening. Silvering is more prominent on peach cultivars such as "Sunbrite" and "Empress" and nectarine cultivars such as "Sunfre" and "Armking" that ripen when adult populations of flower thrips are peaking. In central Georgia, this occurrence is obvious from 15 May to 1 June. Cultivars ripening mid- and late season are unlikely to have silvering problems. Thresholds are desired that would allow spraying of nectarines as needed to prevent excessive silvering injury.

4. Soybean thrips, *N. variabilis*, contribute very little, if any, feeding injury to peach and nectarine fruit.

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