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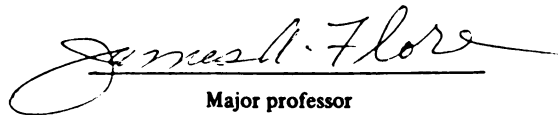
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WHOLE PLANT MEASUREMENT OF PHOTOSYNTHESIS
AND DEVELOPMENT OF APPLE TREES
IN RELATION TO PEST DAMAGE

presented by

Sarah Lynn Breitzkreutz

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of the requirements for

M. S. degree in Horticulture


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**WHOLE PLANT MEASUREMENT OF PHOTOSYNTHESIS AND
DEVELOPMENT OF APPLE TREES IN RELATION TO PEST DAMAGE**

By

Sarah Lynn Breitreutz

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT

WHOLE PLANT MEASUREMENT OF PHOTOSYNTHESIS AND DEVELOPMENT OF APPLE TREES IN RELATION TO PEST DAMAGE

By

Sarah Lynn Breitzkreutz

The objectives of this study were to determine the relationship between whole plant photosynthesis (WPP) and overall growth of apple trees as influenced by the damage caused from insects and disease. WPP was measured on sixty four apple trees of varieties 'Empire' and 'Liberty' seven times during the 1997 growing season on trees subjected to six pesticide and fungicide treatments. Results showed a decrease in the rate of WPP as the season progressed for all treatments from a maximum of $1.5 \mu\text{mol CO}_2 \cdot \text{cm}^{-2} \text{TCSA} \cdot \text{s}^{-1}$ to a minimum of $< 0.5 \mu\text{mol CO}_2 \cdot \text{cm}^{-2} \text{TCSA} \cdot \text{s}^{-1}$. The soft IPM treatments had higher rates of photosynthesis than other treatments during June when the photosynthetic rate was near maximum. WPP was found to be correlated with total foliar damage on three dates of damage assessment for non-barrier 'Empire' and one date for 'Liberty'. Yield was greater for the barrier plot than the non-barrier plot (0.86 and $0.79 \text{ kg} \cdot \text{cm}^{-2} \text{TCSA}$) and greater for 'Empire' than 'Liberty'. In light of the interesting results observed in the photosynthesis between the soft chemicals and the conventional chemicals we repeated the study with potted apple trees. We observed similar results to the field experiment at three sampling dates.

Dedication

This thesis is dedicated to Great Grandma Brazee. I wish she could have been here to see this.

ACKNOWLEDGMENTS

I would sincerely like to thank Mark Kelm for his love, support and friendship. Mark, you're the best! I would also like to thank Mom, Tom, Liz, Grandma Gavitt, Dad and Anita for their encouragement and support.

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LIST OF ABBREVIATIONS

CHES – Clarksville Horticultural Experiment Station
CMD – Cumulative Mite Day
CO₂ – Carbon dioxide
DAFB – Days After Full Bloom
Epan – Class A Pan Evaporation
HRTC – Horticultural Research Teaching Center
IPM – Integrated Pest Management
IRGA – Infrared Gas Analyzer
PAR – Photosynthetic Active Radiation
PLC – Parkinson Leaf Chamber
ppm – Parts Per Million
PVC – Polyvinyl Chloride
TCSA – Trunk Cross Sectional Area
WPP – Whole Plant Photosynthesis

SECTION I

REVIEW OF LITERATURE

Review of Literature

As agriculture developed, humans remodeled the landscape significantly by encouraging some animals and plants to multiply and others to be displaced. The result was local areas with reduced biological diversity and a greater confrontation of humans with insects. Subsequently, when agriculture developed and greater areas of land were utilized for farming, pressure from insect populations increased disproportionately, making pest control a major preoccupation (Pedigo, 1999). The Sumerians are reported to be the earliest to implement pest control strategies with the use of sulfur about 2500 BC Egyptians and Chinese used herbs and oils as insecticides for the protection of seeds and stored grain (Pedigo, 1999). In the 19th century, methods to control orchard pests were lead arsenate and sulfur compounds. Although effective in killing pests, these compounds proved to be extremely toxic to humans (National Research Council, 1993).

Modern use of insecticides began with the advent of 1,1-Bis (4-chlorophenyl)-2,2,2-trichloroethane (DDT) in 1946 (Poehling, 1989). The harmful effects of DDT and its persistence in the environment became known over time, which led to the revocation of DDT in 1972 (National Research Council, 1993). Synthetic pyrethroid compounds began to be used in the 1980's. The advantages were that they offered much the same protection as DDT but could be applied in much smaller amounts (gm rather than kg·acre⁻¹), and that they broke down in the environment (National Research Council, 1993). However, one of the problems with using pyrethroid compounds is that they are indiscriminate

insecticides, killing both beneficial and non-beneficial insects. This disrupts the natural balance of predators and prey in the orchard. Researchers observed the detrimental effects of broad spectrum pesticides such as the development of resistance to formerly lethal compounds, previously harmless pests becoming major pests and people's awareness and concerns with pesticide residues in their produce and their possible harmful effects (Croft, 1978). Further disadvantages with broad spectrum pesticides were biomagnification of pesticides in the food chains, and increased cost for production of crops due to increased costs of pesticides (Watson et al., 1975).

Many of these environmental problems have arisen because many horticultural crops such as apples are long term perennial crops. Orchards are in the same location for many years and with repeated application of pesticides, fungicides and herbicides there is an accumulation of chemicals that persist in the soil. Also, apple orchards are usually located near large bodies of water such is the case in Oregon, Washington, Michigan and New York because of the favorable climate and good drainage in these locations. This can lead to magnification of the impact of orchard pesticides on these associated water systems (Croft, 1978).

Integrated pest management

Integrated pest management (IPM) is the practice of manipulating insect or disease pest populations using ecologically sound methods of control to keep these pests at levels below that which would cause economic injury (Watson et al., 1975). The increased use of IPM strategies has been brought about for three

main reasons: 1) insect and disease resistance to pesticides, 2) consumer demands for insecticide residue free foods and 3) the loss of the use of existing chemicals because of federal regulations (Subrahanyam and Hagstrum, 1996). As the name implies, IPM practices involve chemical controls, biological controls and cultural practices. Biological controls consist of: predators, parasites and pathogens (VanLenteren, 1989). The objective of a biological control is either to introduce natural enemies or to manipulate existing ones to cause the pest population to fall to a density below the economic-injury level (Pedigo, 1999). A goal of many biological control programs is to create a self-sustaining system. This means that there has to be a balance maintained between the natural enemy and the pest. The pest can't be completely eliminated because this would deplete the source of food for the natural enemy. Therefore a balance must be struck between the populations of the natural enemy and the populations of the pest (Pedigo, 1999).

One of the first IPM programs was developed in Nova Scotia in 1942. Export restrictions forced apple growers in this region to implement a program that reduced pesticides. They attempted to regulate natural pest populations and limited the use of selective insecticides such as Ryania, nicotine, and lead arsenate. The adoption of this new system saved the industry in Nova Scotia (Whalon and Croft, 1984).

A major concern when reducing chemical input in orchards is to ensure that fruit quality is not compromised. One percent damaged fruit is the maximum allowed for all pest and non-pest related sources for fresh market in the United

States (Croft and Hoyt, 1983). There are four categories for apples in the U.S. (U.S. extra fancy, U.S. fancy, U.S. No.1 and U.S. utility). For an apple to be classified as extra fancy, it must meet the following criteria: mature but not overripe, clean and well formed. Free from decay, internal browning, internal breakdown, scald, scab, bitter pit, Jonathan spot, freezing injury, visible water core, and broken skins and bruises. Free from injury caused by smooth net-like russeting, sunburn or spray burn, limb rubs, hail, drought spots, scars, disease, insects, damage by smooth, solid, slightly rough or rough russeting or stem or calyx cracks, and free from damage by invisible water core after January 31st of the year following the year of production. In addition, each apple of this grade must have the amount of color specified in table 51.305 for the variety. (Code of Federal Regulations, 1996). Because of this low tolerance, IPM practices are difficult to use.

For IPM to be successful, it has to be economically feasible. Managing an orchard should include attention to all major types of pests (insects, diseases, weeds and vertebrates) and their principal natural enemies. Farmers need to know what insects and diseases are problems in their location and the life cycles of these pests. IPM requires much more technical expertise than spraying chemicals according to a schedule. The grower needs to know precisely what the pests are doing, in addition, they need to know which beneficial insects are present and how to manage these populations by modifying pesticide applications (Croft, 1978).

Management of the habitat encompassing the orchard is very important. This habitat is comprised of soil, trees, ground cover and the vegetation and nonliving matter surrounding the orchard. The proximity of plants harboring key orchard pests can have a profound effect on the probability of key pests immigrating into and colonizing an orchard (Prokopy, 1994).

IPM has been equated to steps of a ladder. The first of those steps being control of a single class of pests using ecologically sound methods. The second is the integration of multiple management practices across all classes of pests. The third step of the ladder is the integration of IPM for all classes of pests with all the horticultural practices used on a farm. Finally the fourth step is the blending together of concerns about pest management of all the interested parties including researchers, extension personnel, private consultants, industry, growers, processors and distributors, consumers, neighbors of growers, environmentalists and local as well as federal government regulatory agencies (Prokopy et al., 1994).

When determining where we are today in terms of implementing the four levels of IPM designed by Prokopy, it would probably have to be said that we are still on stage one of trying to control single classes of pests. There are several reasons for this which have to do with government policies influencing farm profits, insurance and credit. Also the economic viability of alternative techniques such as yield and profits, the size of the farm, and the increased labor and management needed for alternative techniques (McDonald et al., 1994). In addition, there are the farmer's preconceptions about alternative means of

growing. Recent studies have shown that most farmers have incorporated some form of IPM into their orchard practices. A survey of growers in the New England area reported that 73% of apple growers currently scout for insects and disease before spraying chemicals. In addition, 15% of apple growers in New York reported using all of the IPM methods available for their crop (McDonald et al., 1994). However, even though this sounds promising, many farmers do not wait for thresholds to be reached before spraying the crop (McDonald et al., 1994).

Damage Thresholds

Damage threshold is defined as the amount of injury that justifies some form of control measures. Economic threshold and action threshold are both defined as the amount of damage that justifies the cost of artificial control measures. These thresholds are usually expressed as a number of insects per area, plant or sampling procedure. Less commonly these levels are expressed as degree of plant damage or combinations of numbers and damage (Pedigo, 1999). Pests that feed on the foliage are particularly suitable to IPM practices (Francesconi, et al., 1996a). Damage thresholds are difficult to determine because of many factors such as the leaf to fruit ratio, weather, variety, time of year, and tree vigor.

Timing and severity of injury is very important in the development of damage thresholds. Early defoliation of spur leaves in apples was found to reduce fruit set and fruit development (Ferree and Palmer, 1982). Lakso (1984) showed that defoliation of spur leaves results in severe reductions in fruit set while defoliation of shoot leaves have relatively little effect. Removing spur

leaves later in the season [after 30-50 days after full bloom (DAFB)] has no effect on fruit size (Rom and Ferree, 1986). Infection from diseases can effect photosynthesis. Powdery mildew (*Podosphaera leucotricha*) caused a 75% reduction in photosynthesis at 35 days after infection. Apple scab (*Venturia inaequalis*) caused a 20% decrease in photosynthesis (Ferree et al., 1986). Infestation by mites was found to cause reduction in photosynthesis. A population of 60 mites per leaf caused a significant reduction in apple photosynthesis three days after placement on the leaf. Nine days after infection, 15 mites per leaf reduced photosynthesis by 26%, 30 mites per leaf by 30% and 60 mites per leaf by 43% below the value observed in uninfected controls (Ferree et al., 1986). Francesconi et al. (1996b) found an interaction between cumulative mite day (CMD) and reduction in fruit weight from trees with high CMD and normal crop load. Weddle (1990) looked at the balance of beneficial predator mites to phytophagous mites and found that a ratio of 2:10 was sufficient to reduce the number of miticide sprays applied. Weddle also looked at the timing of pesticide applications. He found that spraying for pear psylla (*Homoptera: psyllidae*) in the dormant season controlled pear psylla for the season without killing beneficial arthropods that would normally have been killed by the chemical if applied later in the growing season.

In addition to the habitat surrounding the orchard and the pests in the orchard, it is important to understand the horticultural practices that can aid in pest management. For example, maintaining tree stability in the soil to promote the establishment of a strong root system, ensuring that there is adequate

nutrient and moisture availability for tree and fruit growth, and pruning trees in a way that optimizes fruit yield and quality (Prokopy, 1994). All of these factors give rise to a tree that is in good physiological status.

Some problems with damage thresholds are that they are poorly defined or not available. The variations in the thresholds comes from differences in sampling techniques, pest status, market parameters, management options, time of year of control, orchard history, and human factors (e.g. perception of pest and management philosophy) (Whalon and Croft, 1984). For example, Prokopy et al. (1997) explained that monitoring of tentiform leafminer is dependent upon which generation you want to control (there usually being three generations per year). The most popular is to look for mines on leaves. This is a good method for post petal fall application of pesticide but too late for petal fall or pre-bloom applications which destroy adults, eggs and sap feeding larvae. They found that pre-bloom captures of leafminer adults were useful predictors for growers to determine if action in the form of chemical sprays needed to be taken or not.

Monitoring for disease should be based on the right conditions for the disease to develop. Apple scab is a good example of this. The use of spore traps and various weather instruments makes it possible to monitor both the scab fungus and the climatic factors inducing infection. Therefore, when the apple scab ascospores are detected and the right weather conditions develop sprays can be applied and if those conditions don't develop, then the sprays can be avoided (Jones, 1974). One problem with monitoring and spraying pesticides for individual pests is the effect on other pests beneficial or non-beneficial. When

applying fungicides, the targeted disease is not the only one affected. For example, some fungicides have an effect on mite populations, killing beneficial mites (Jones, 1974).

Simulated pest injury or stress can be a very good tool for understanding the periods of the growing season that are particularly sensitive to decreases in photosynthesis and also in developing damage thresholds. Disegna (1994) studied the effect of Sinbar (an herbicide that interrupts the flow of electrons from photosystem II to photosystem I) applied to apple trees at different times in the growing season and at different concentrations. He found that at 15 and 30 DAFB, fruit were induced to abscise. This was greater for trees having a high crop load. Inhibition of photosynthesis at 30, 60, 80, and 100 days after full bloom reduced return bloom. Partial defoliation below a certain threshold may be overcome by plant photosynthetic compensation. Evidence shown by Layne and Flore (1992) in cherry showed that up to 20% of leaf area could be removed between veins without reducing whole leaf photosynthesis. Hall and Ferree (1976) found that reductions in apple leaf area up to 7.5% had no effect on photosynthesis, however when leaf area losses exceeded 10%, significant reductions in photosynthesis were observed.

The use of models can be helpful in determining damage thresholds and make IPM more accessible to the grower. Developing a model for disease and pests would give up to date information to growers to make day to day decisions on disease and pest control. The data from these models has to be reliable and current. For example fungicides for scab control (a major disease of Michigan

apples) must be applied 24-36 h from the beginning of a wetting period (Jones, 1976). PETE (Predictive Extension Timing Estimator) was one of the first models for generalized individual phenology timing. This model sought to improve phenology predictions of pest developmental stages based on synchronization with biological monitoring information from the field (Whalon and Croft, 1984).

Whole plant photosynthesis

As discussed above there is need for more accurate ways to determine damage thresholds especially for secondary pests that feed only on the foliage of the crop. One tool used to estimate the effect of damage done by foliage feeders is to measure the photosynthetic capacity of the leaves. This can be done on the single leaf or the whole plant level. Previously whole plant photosynthesis systems were cumbersome and rarely portable. With the advent of new materials such as Mylar[®], movement of the system from one tree to the next has become much easier. There are many benefits in measuring whole plant photosynthesis rather than single leaf photosynthesis. The main reason is due to the variation between leaves in a canopy. When measuring single leaf photosynthesis, only a selection of leaves can be measured on a tree which have to be extrapolated to encompass photosynthesis of all leaves on the tree. This can lead to over or under-estimation of the photosynthetic capacity of the entire tree. WPP is the integration of photosynthesis of all the leaves on a tree and respiration by branches, and fruit.

Whole plant photosynthesis (WPP) rates are much lower than those for single leaf for many reasons. One is due to leaf age. In a tree canopy there are

newly formed leaves that have not yet reached their maximum photosynthetic capacity, fully expanded leaves at their full photosynthetic potential and older leaves that have begun the process of senescence (Poni et al., 1994a). Differences in angles of incident radiation vary depending on the position of the leaf, whether it is at the top or bottom of the canopy or on which side of the tree. These differences lead to different levels of photosynthesis (Flore and Lakso, 1989). In addition, if the leaf is on the inside of the canopy or the outside there are differences in the amount of light received due to shading effects (Flore, 1994). The respiration of vegetative and reproductive tissues also must be considered when determining whole plant photosynthesis (Corelli-Grappedelli and Manganini, 1993). Another factor causing variation in photosynthesis among leaves on a tree is crop load. The amount of fruit per tree or absence of effects photosynthesis. Whether the crop load is high or low will make a significant difference on the rate of photosynthesis (Lakso et al., 1996). Also the proximity of carbohydrate sinks and other source-sink relationships play a role in the rate of photosynthesis for a leaf (Edson, 1995). Fujii and Kennedy (1985) observed that after canopy development, there are higher rates of photosynthesis in fruiting trees than non-fruiting trees during the period of rapid increase in fruit growth. Also, toward the end of vegetative period the leaves of fruit-bearing shoots showed a slightly higher rate of photosynthesis, whereas, leaves of shoots without fruits showed a reverse trend (Ghosh, 1973). Grape vines showed a decline in photosynthesis earlier in the day for non-fruiting vines possibly resulting from carbohydrates building up faster in the non-fruiting vine due to

feedback inhibition (Downton et al., 1987). There are also biotic and abiotic stresses that play a role in the rate of photosynthesis for a leaf such as insects, cultural practices, water deficiency or water excess. As demonstrated by the examples above it can be extremely difficult to extrapolate the gas exchange for a single leaf to that of the whole plant.

Heinicki and Childers (1937) were of the earliest to measure WPP. They realized that the measurement of a single leaf or part of a leaf was not representative of the entire plant. With this knowledge they designed a chamber to contain an apple tree and measured the daily photosynthesis for an entire growing season. They found that the plant reached a high rate of photosynthesis early in the season and a maximum rate of photosynthesis was reached while new leaves continued to develop and grow. They also found that the rate of photosynthesis for the whole tree was considerably less than the average based on determinations of single leaves exposed to good light. They estimated that 90% of the total leaves were functioning at a very low rate on many days during the growing season. In addition, they found that with greater transpiration, there was less photosynthesis. With light conditions the same in July and August, there was more photosynthesis in July than August. This they thought was because the plant was losing too much water during the hot part of the summer and closing the stomata during the hot part of the afternoon.

In a similar study Giuliani et al. (1997b) looked at the canopy level relationships between diurnal trends of environmental variables and photosynthetic and transpirational activities and the control exerted by plant

factors on these responses. They observed the WPP of a fruiting and a non-fruiting apple tree to see how source-sink relationships affect the regulation of whole canopy gas exchange. They found that the light-saturated net photosynthetic rates were higher for the fruiting canopy than for the non-fruiting canopy. Also there was a decrease in the afternoon, particularly for the non-fruiting canopy. They believed that the afternoon decrease in photosynthesis was not regulated by stomata as Heinicki and Childers thought, but rather by some other factors, perhaps feedback inhibition. Canopy conductance was higher for the fruiting canopy than the non-fruiting canopy. From this they concluded that canopy conductance may actively regulate photosynthetic activity and may also be modulated by feedback control in response to assimilation capacity. They concluded that adjustments in canopy conductance, which were partially dependent on the vegetative-reproductive status of the tree, control the equilibrium between photosynthesis and transpiration.

A study by Francesconi et al. (1996a) showed that the physiological status of the plant plays an important role in its ability to overcome pest infestation. For example, lightly cropped trees were able to deal with mite infestations better than normally cropped trees as the normal cropped trees showed a reduction in fruit weight with increased mite injury.

For all of the benefits of measuring whole plant photosynthesis there are drawbacks as well. First, the whole plant chambers can be cumbersome. Also more time is involved with setting up the system making it impossible to make as many measurements in one day as can be accomplished when measuring single

leaves. The relationship between the CO₂ differential for a whole tree and the leaf area of the tree is important but very difficult to determine. For example, when measuring older trees, it is extremely time consuming and tedious to count the total number of leaves on the tree and measure their areas. It is possible that whole plant gas exchange can be based on different criteria such as the amount per plant in a given period of time (Miller et al., 1996) or on the basis of cross sectional area of the plant or total shoot length (Palmer, 1987).

WPP can possibly be used as a tool to determine damage thresholds. With knowledge of times during the growing season that are particularly sensitive to decreases in photosynthesis and the interaction with crop load we can attempt to understand the amount of damage that can occur before the need for some type of action.

SECTION II

WHOLE PLANT MEASUREMENT OF PHOTOSYNTHESIS AND DEVELOPMENT OF APPLE TREES IN RELATION TO PEST DAMAGE

Introduction

Biotic and abiotic stresses can severely damage the fruit or vegetative organs of apple trees. The amount of damage incurred by a plant before it affects dry matter accumulation or a reduction in fruit quality is termed a damage threshold. Economic threshold and action threshold are both defined as the amount of damage that justifies the cost of artificial control measures (Pedigo, 1999).

Pests that attack fruit have a lower damage threshold than pests that feed on the foliage. Therefore, a major concern when reducing chemical input is to ensure that fruit quality is not compromised. For example, there are four grades for apples in the U.S. (U.S. extra fancy, U.S. fancy, U.S. No.1 and U.S. Utility). There are strict guidelines that must be met for an apple to be categorized as an extra fancy explained in the Code of Federal Regulations (1996). One percent damaged fruit is the maximum allowed for all pest and non-pest related sources for fresh market (Croft and Hoyt, 1983). Pest management strategies which keep fruit damage at low levels are difficult to use.

Diseases and insects that attack the foliage of a tree are especially suitable for IPM practices if pests can be controlled after a certain tolerable level of leaf injury occurs and before the crop is damaged (Francesconi et al., 1996a). However, quantifying the damage caused by foliar feeders on perennial crops like apple is difficult. There are many integrated factors which determine damage thresholds such as environment (availability of water, nutrients and sunlight), biotic (insects, diseases and weeds), cultural practice (pruning and spacing), and

physiological (vigor, crop load, and return bloom). Foliar pests effect the production and allocation of carbon resources in the whole plant. Therefore, duration and timing of injury are very important and may reduce the carbon assimilation potential of the tree (Layne and Flore, 1992).

The relationship between photosynthesis and damage was observed by Disegna (1994) in an experiment using a photosynthetic inhibitor. When applied to apple trees at 15 and 30 DAFB, fruit abscission was induced. This was markedly higher for trees having a high crop load vs. a low crop load, and also significantly reduced yield and fruit size. Francesconi et al. (1996b) showed that an increase in apple crop load was associated with an increase in sensitivity of apple trees to high mite populations as measured by mean fruit size and crop value. Effects of simulated insect injury to apple leaves were studied by Hall and Ferree (1976). Losses up to 7.5% did not effect leaf photosynthesis, but above 10% significant reductions occurred. Further evidence shown by Layne and Flore (1992) in cherry showed that up to 20% of leaf area could be removed between veins without reducing whole leaf photosynthesis.

The need for reliable damage thresholds and the use of IPM has become very important for three main reasons: 1) insect and disease resistance to pesticides, 2) consumer demands for pesticide residue free foods and 3) the loss of the use of existing chemicals due to federal regulations (Subrahanyam and Hagstrum, 1996). The development of accurate damage thresholds can aid the farmer in making informed decisions on when to apply pesticides.

The physiological status of the plant plays an important role in its ability to overcome pest infestation. Pest damage can effect fruit development mediated via the carbon balance of a tree (Lakso et al., 1996). WPP is an estimate of the total net carbon uptake of whole plants and, therefore, could be used as a tool to estimate the physiological status and damage thresholds for a plant. Francesconi et al. (1996b) found a correlation between crop load and WPP per fruit and showed that crop load greatly effected the sensitivity of apple trees to European Red Mite.

The objectives of the current study were to correlate WPP with pest damage and yield in several new pest management systems. This study was carried out by measuring whole plant gas exchange on trees in two orchard pest systems and assessing the foliar damage caused by pests on these trees.

Materials and Methods

Damage threshold research was conducted on plots designed to evaluate whole orchard pest management systems at the Clarksville Horticulture Experiment Station (CHES), Clarksville, MI and at the Horticulture Research and Teaching Center (HRTC), East Lansing, MI. One main field experiment (1997 CHES) and one container-grown plant experiment (1999 HRTC) were conducted. WPP was measured and correlated to foliar damage due to pests or to crop yield in an effort to determine damage thresholds for apple. The plant material and measurement techniques are described below.

1997 Experiment at CHES

Plant Material

The CHES IPM apple project was established in 1994. Two apple varieties, 'Empire'/M.9 EMLA and 'Liberty'/Mark (Hilltop Nurseries, Hartford, MI), were used in this experiment (Fig. 1). The trees were trained to a slender spindle system. Each tree was supported by a 2.5 m metal tube and with high tensile wire, at a 2 m height, which was anchored at both ends of each row. Eight 0.4 ha plots with 300 trees/plot were separated by at least 200 m and were divided into two main treatments. Four of the plots were surrounded with a vegetative barrier which consisted of hybrid poplar (*Populus deltoides* Bartr. X *P. nigra* L.), adjacent to the apple trees, Italian alder (*Alnus cordata* L.), and white pine (*Pinus strobus* L.), furthest from the apple trees. Four plots had no a barrier. Orchard and barrier trees were watered with a drip irrigation system at 60% of class A pan evaporation (Epan) throughout the season. Alley-ways in the barrier plot were

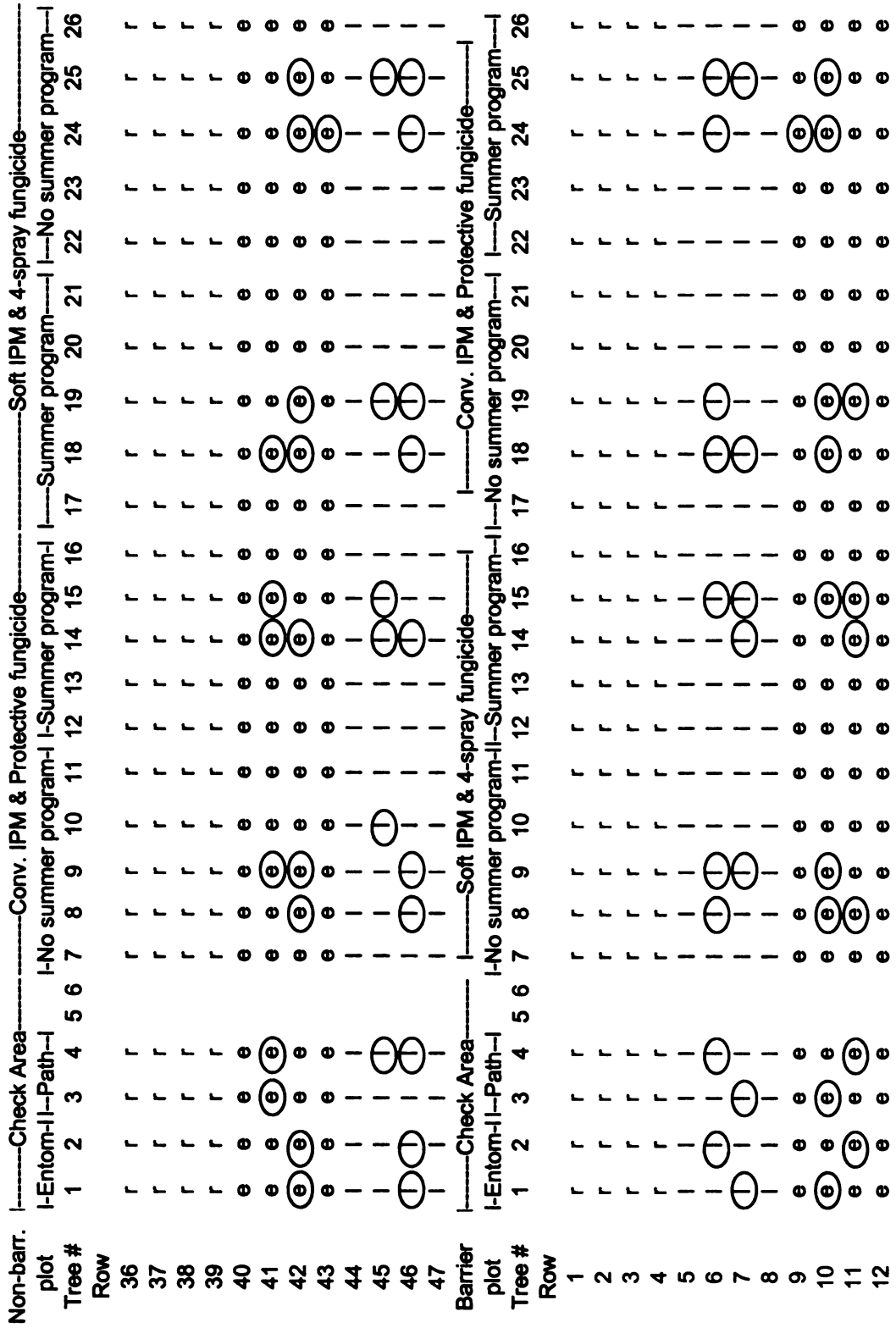


Figure 1. Plot plan for Non-barrier and Barrier plots at CHES, Clarksville, MI 1997. r=Idared, e=Empire, and l=Liberty
 Note: Circled trees were those used in the experiment.

planted with an endophytic grass mix, "Crusader" (Seed Research of Oregon, Inc., Corvallis, OR), that included a rye grass inoculated with a fungal endophyte *Acremonium lolii*, which has been shown to be insecticidal (Johnson-Cicalese and White, 1990). The non-barrier plot was established without perimeter barriers and with standard Kentucky blue/fescue grass for sodded alley-ways. Weed control consisted of Weedar[®] 64, Solicam[®], and Roundup[®] to control broadleaf weeds and rogue grasses. The pest management treatments were established perpendicular to the apple variety rows.

Pest Management System in each plot

The pest management system consisted of six treatments; 1) Entomology control in which no insecticides or fungicides were used; 2) Pathology control in which Guthion[®] 50W was applied but no fungicides were applied; 3) Soft IPM with four sprays of the fungicides Dithane[®] 75DF and Elite[®] 45DF and summer applications of Fluazinam (a non-registered pyridine fungicide); 4) Soft IPM with four sprays of fungicides Dithane[®] 75DF and Elite[®] 45DF with no Fluazinam; 5) Conventional IPM with protective fungicide Dithane[®] 75DF and no Fluazinam; 6) Conventional IPM with protective fungicide Dithane[®] 75DF and summer applications of Fluazinam. In addition, the soft IPM treatments had applications of Confirm[®], Spinosad[®] and Provado[®] 1.6E.C. The conventional IPM had applications of Lannate[®] 90SP, Lorsban[™] 50W and Guthion[®] 50W. In addition, Agri-Mycin[®] 17, Agri-strep[®], NAA and Mous-Con[®] were applied to all six of the above treatments. The border trees were sprayed with Asana[®] (Table 1).

Table 1. Pest and pathogen control for barrier and non-barrier plots, at IPM apple orchard site in Clarksville Horticultural Research Experiment Station, Clarksville, MI 1997.

Pesticide Application Date	Treatment		
	Entomology Control	Pathology Control	Soft IPM + Summer Program
21-Apr			
29-Apr			Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha
07-May	*Weedar [®] 64, 2.4l/ha	*Weedar [®] 64, 2.4l/ha	*Weedar [®] 64, 2.4l/ha
06-May			
10-May			Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha
13-May			
20-May	Agri-Mycin [®] 17,1.7kg/ha	Agri-Mycin [®] 17,1.7kg/ha	Agri-Mycin [®] 17,1.7kg/ha
23-May			Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha
27-May			
28-May	Agristrep [®] ,1.7kg/ha	Agristrep [®] ,1.7kg/ha	Agristrep [®] ,1.7kg/ha
03-Jun			Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha
04-Jun	NAA, 7ppm	NAA, 7ppm	NAA, 7ppm
05-Jun			Spinosad [®] , 0.37l/ha
06-Jun			Provado [®] 1.6EC, 0.35l/ha
11-Jun	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
16-Jun			Fluazinam, 0.43l/ha
26-Jun		Guthion [®] 50W, 1.4kg/ha	
27-Jun			Fluazinam, 0.43l/ha
07-Jul			Confirm [®] , 1.33l/ha Fluazinam, 0.43l/ha Spinosad [®] , 0.37l/ha
15-Jul	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha
18-Jul			Fluazinam, 0.43l/ha
27-Jul			Fluazinam, 0.43l/ha
29-Jul	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
06-Aug			Fluazinam, 0.43l/ha
08-Aug		Guthion [®] 50W, 1.4kg/ha	Confirm [®] , 1.33l/ha
20-Aug	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
26-Aug		Guthion [®] 50W, 1.4kg/ha	Confirm [®] , 1.33l/ha
03-Nov	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha
24-Nov	Mous-Con [®] ,11.3kg/ha	Mous-Con [®] ,11.3kg/ha	Mous-Con [®] ,11.3kg/ha

Table 1.
Continued

Pesticide Application Date	Treatment		
	Soft IPM - Summer Program	Conventional IPM + Summer Program	Conventional IPM - Summer Program
21-Apr		Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
29-Apr	Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha	Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
07-May	*Weedar [®] 64, 2.4l/ha	*Weedar [®] 64, 2.4l/ha	*Weedar [®] 64, 2.4l/ha
06-May		Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
10-May	Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha		
13-May		Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
20-May	Agri-Mycin [®] 17,1.7kg/ha	Agri-Mycin [®] 17,1.7kg/ha Dithane [®] 45DF, 4.1kg/ha	Agri-Mycin [®] 17,1.7kg/ha Dithane [®] 45DF, 4.1kg/ha
23-May	Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha		
27-May		Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
28-May	Agrestrep [®] ,1.7kg/ha	Agrestrep [®] ,1.7kg/ha	Agrestrep [®] ,1.7kg/ha
03-Jun	Elite [®] 45DF, 0.27l/ha Dithane [®] 75DF, 2.1kg/ha	Dithane [®] 45DF, 4.1kg/ha	Dithane [®] 45DF, 4.1kg/ha
04-Jun	NAA, 7ppm	NAA, 7ppm	NAA, 7ppm
05-Jun	Spinosad [®] , 0.37l/ha		
06-Jun	Provado [®] 1.6EC, 0.35l/ha	Lannate [®] 90SP, 1lb/A Lorsban [™] 50W, 2lb/A	Lannate [®] 90SP, 1lb/A Lorsban [™] 50W, 2lb/A
11-Jun	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
16-Jun		Fluazinam, 0.43l/ha	
26-Jun			
27-Jun		Fluazinam, 0.43l/ha	
07-Jul	Confirm [®] , 1.33l/ha Spinosad [®] , 0.37l/ha	Guthion [®] 50W, 1.4kg/ha Fluazinam, 0.43l/ha	Guthion [®] 50W, 1.4kg/ha
15-Jul	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha	*Roundup [®] , 3.6l/ha *Weedar [®] 64, 2.4l/ha
18-Jul		Fluazinam, 0.43l/ha	
27-Jul		Fluazinam, 0.43l/ha	
29-Jul	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
06-Aug		Fluazinam, 0.43l/ha	
08-Aug	Confirm [®] , 1.33l/ha	Guthion [®] 50W, 1.4kg/ha	Guthion [®] 50W, 1.4kg/ha
20-Aug	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha	*Roundup [®] , 3.6l/ha
26-Aug	Confirm [®] , 1.33l/ha	Guthion [®] 50W, 1.4kg/ha	Guthion [®] 50W, 1.4kg/ha
03-Nov	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha	*Roundup [®] , 3.6l/ha *Solicam [®] 3.4kg/ha
24-Nov	Mous-Con [®] ,11.3kg/ha	Mous-Con [®] ,11.3kg/ha	Mous-Con [®] ,11.3kg/ha

Note: Asana at .74l/ha was applied to vegetative barrier trees on 6/5, 7/7, 8/8, and 8/26/97.

*Roundup, Weedar and Solicam were herbicides applied to ground beneath trees and alleyways.

Whole Plant Photosynthesis

Methodology: WPP was estimated using a balloon methodology as previously reported by Miller et al. (1996) with a chamber constructed from Mylar® designed to fit over the entire canopy of the apple tree. Mylar® was chosen because it is lightweight, has low permeability to CO₂ and water vapor, and the transmission characteristics are very similar to air through the visible range, with nearly zero transmission below 314 nm in the UV range (E. I. du Pont de Nemours and Company, 1999). Our light transmission experiments supported their findings and, furthermore, we found that transmission of infrared was nearly 100% (Fig. 2).

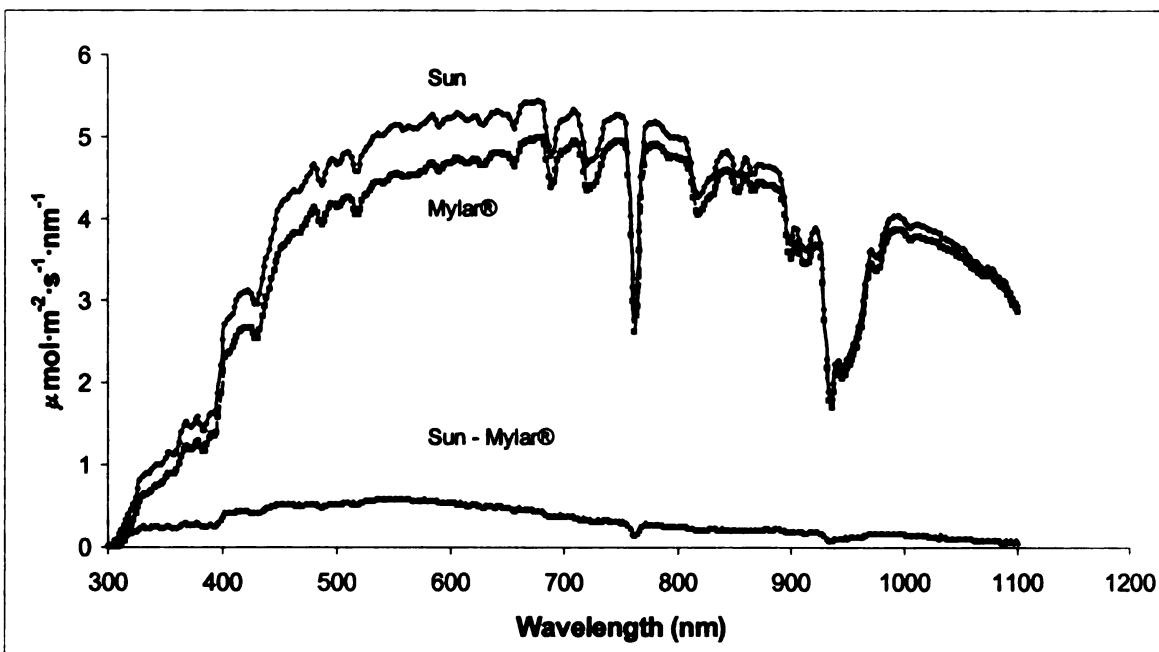


Figure 2. Spectrum for Mylar®

Mylar's® ability to transmit infrared light is important because it prevents heat build up inside the chamber, which is caused by trapped infrared radiation. Additionally, Mylar® is resistant to high and low temperatures and is strong yet flexible and puncture-resistant. A 4 m³ chamber was fitted over the entire canopy of an apple using zippers to seal the side and top. The Mylar® chamber was attached to a 0.28 m² wooden circular base that was clamped around the tree trunk with brass trunk clamps (Fig. 3). A hole was cut in the wooden base to fit a 10.2 cm diameter piece of polyvinyl chloride (PVC) pipe with an elbow joint fitted to a 1.2 m piece of PVC pipe. Air was circulated through the system with a shaded pole blower model number 4C004A (Dayton Electronic Mfg. Co., Niles, IL) attached to the end of the PVC pipe. The speed of the fan ranged from 600-3000 l/min and was controlled with a variable autotransformer type 3PN1010 (Staco energy Products Co., Dayton, OH).

The gas exchange for the whole tree was measured with an infrared gas analyzer (IRGA) ADC LCA-2 (Analytical Development Co., Hoddesdon, U.K.). The amount of CO₂ in the air entering the chamber was measured from inside the PVC pipe and termed the reference air. The amount of CO₂ in the air exiting the chamber was measured from a 7 cm hole cut in the top of the chamber and was termed the sample air. The air flow through the system was adjusted to stay within 5-30 ppm Δ CO₂ while still allowing for enough flow to keep the air temperature inside the chamber from increasing (approximately three complete air exchanges per minute). This flow rate was measured with a Tri-Sense® hot wire anemometer (Cole Parmer, Vernon Hills, IL). The equation to estimate

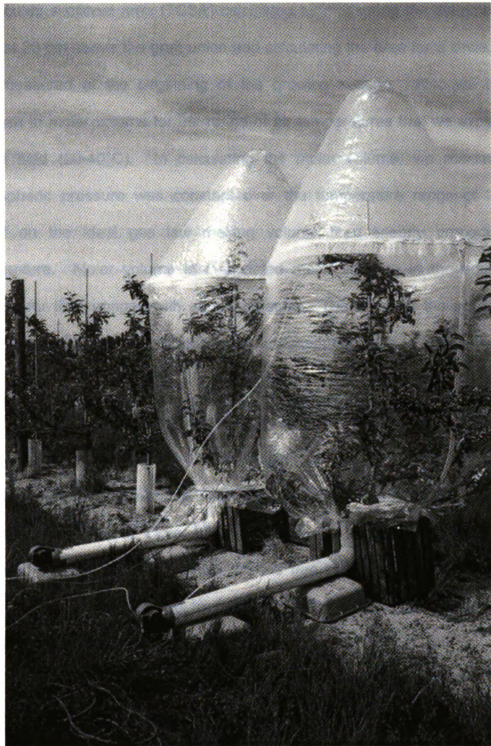


Figure 3. Two whole plant photosynthesis chambers.

WPP was taken from Miller et al. (1996) and modified to include division by the trunk cross sectional area (TCSA) calculated by measuring the diameter of the trunk at 20 cm above the graft union and calculating the area for a circle. TCSA was measured at the beginning of the growing season. Also we included changes in molar volume for the range of air temperatures that we experienced in the field (20-40°C). In calculating the molar volume, we assumed that atmospheric pressure was constant over the temperature range of 20-40°C based on the ideal gas law making volume then linearly proportional to temperature. Molar volume is designated molar volume_T in the equation to account for the changes with air temperature. The units for the equation are $\mu\text{mol CO}_2 \cdot \text{cm}^{-2} \text{TCSA} \cdot \text{s}^{-1}$. Hence, the revised equation is:

$$P_n(\mu\text{mol CO}_2 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}) = \frac{(\Delta\text{CO}_2)\mu\text{L} \cdot \text{L}^{-1} \times (\text{flow})\text{L} \cdot \text{min}^{-1}}{\text{molar volume}_T \mu\text{L} \cdot \mu\text{mol}^{-1} \times (\text{TCSA})\text{cm}^2 \times 60\text{s} \cdot \text{min}^{-1}}$$

Leaf area was calculated on a sample of 20 leaves per tree by measuring the length of the lamina, the width at the widest region of the leaf, and multiplying by 0.71 (J.A. Flore, unpublished data). The average leaf area was multiplied by the number of leaves on the tree to get a total leaf area. The equation above can be used to calculate WPP on the basis of leaf area by substituting leaf area in m^2 for TCSA.

In addition to the gas exchange measurements, the incident photosynthetic active radiation (PAR) was measured with a 190S quantum sensor and recorded with a LI-1000 data logger (LI-COR, Inc., Lincoln, NE). The sensor was held above the canopy in a horizontal position to the ground. Air

temperature was measured with copper-constantan thermocouples (type T) (OMEGA Engineering, Inc., Stamford, CT) placed at the inlet and outlet of the chamber. Relative humidity was measured with the ADC LCA-2 Parkinson leaf chamber (PLC) (Analytical Development Co., Hoddesdon, U.K.) by placing the opened PCL at the inlet and outlet of the chamber.

CO₂ exchange: Sixty four trees were chosen for WPP measurements which consisted of two trees from each control treatment and three trees from each of the remaining treatments from each variety and from the barrier and non-barrier plot. CO₂ exchange measurements were determined for each tree at seven dates throughout the 1997 growing season. The first measurement was at petal fall (6/8/97), the second at fruit diameters 18-22 mm (6/28/97), and the third through the seventh measurements were determined at full canopy development (7/9, 7/25, 8/6, 8/30 and 9/16/97, respectively). The sample air and reference air were sampled three times for each tree at approximately 15 min intervals and averaged. We allowed about five minutes to pass before taking measurements on each tree to ensure that all of the air from the last tree had flushed through the system. The PAR, relative humidity and temperature were taken at every third measurement or more frequently on partially cloudy days.

Entomology Measurements

On July 22, August 28 and October 15, 1997 entomologists from the Department of Entomology at Michigan State University evaluated damage caused by insects on each of the experimental trees. The number of mines from the Spotted Tentiform Leafminer, *Phyllonorycter spp.*, was determined by a one

minute visual search of the canopy. The amount of feeding from Lepidoptera, mainly Oblique-Banded Leafroller, *Choristoneura rosaceana* (Harris), was determined by a one-minute search of the shoots. To determine the amount of damage caused by Rosy Apple Aphids, *Dysaphis plantaginea* (Passerini), a one-minute visual inspection of the shoots was performed. Aphid damage was identified on emerging shoots as well as by the incidence of stunted leaves, cupped leaves and deformed shoot growth. The amount of bronzing and burning caused by European Red mite, *Panonychus ulmi* (Koch), and white apple leafhopper, *Typhlocyba pomaria* (McAtree), was ranked on a scale of 1-5 depending on severity with one being least severe and five being the most severe.

Yield

Fruit was harvested on September 24-26, 1997 and kept separate by tree. The fruit was separated into categories by weight (>270, 215-270, 170-215, 130-170, 95-130 and <95g), and the number and weight of fruit in each category were recorded.

Damage thresholds

WPP was correlated with the damage assessments and yield. The damage assessments for individual pests were added to get total foliar damage. This total foliar damage was then graphed against WPP. Individual pest numbers were also graphed against WPP. The final measurement of WPP (9/16/97) was correlated with the average yield per tree.

1999 Experiment

Plant Material

The experiment included 30 one-year-old 'Empire'/M26 apple trees. The trees were planted on April 22, 1999 in three-gallon pots with sterilized sandy loam soil from the greenhouse of Michigan State University. The trees were headed back to two lateral shoots per tree at the time of planting and transported to the Horticultural Teaching and Research Center where they were placed on a gravel pad approximately 2 m apart. The plants were kept well watered and each tree was fertilized with 4.5 gm of 20N:20P:20K at two weeks intervals.

Pesticide Treatments

Treatments were arranged in a completely randomized design with three treatments: 1) a control in which no pesticides were sprayed; 2) a soft IPM treatment with four sprays applied at weekly intervals of the fungicides Elite[®] 45DF at 0.2 ml/l and Dithane[®] F45 at 1.3 ml/l followed by one spray of the insecticides Spintor[™] 25C at 0.2 ml/l and Provado[®] 1.6F at 0.2 ml/l; 3) a conventional treatment with four weekly sprays of the fungicide Dithane followed by one spray of the insecticides Lannate[®] 90SP at 0.6 ml/l and Lorsban[™] 4EC at 0.6 ml/l. There were ten replicates of each treatment for a total of 30 trees.

Whole Plant Measurements

Following the last application of pesticides, whole tree CO₂ exchange was estimated. The design for measuring WPP was the same as described earlier for the 1997 experiment except that the chamber had a smaller volume and the wood base had a smaller diameter. The number of air exchanges per minute

was approximately 2.5. The gas exchange system used was the CIRAS-1 (P.P. Systems, Haverhill, MA). The air flow through the system was measured by the time required to fill a polyethylene bag of known volume with the air exiting from the outlet of the chamber as described by Giuliani et al. (1997b). In addition to WPP, single leaf photosynthesis was measured using the CIRAS-1 with the leaf chamber attached. The incident PAR and temperature were measured using the same procedures as in 1997.

RESULTS

1997 Field Experiments.

Rate of photosynthesis declined as the season progressed from a maximum of $1-5 \mu\text{mol CO}_2 \cdot \text{cm}^{-2} \text{ TC SA} \cdot \text{s}^{-1}$ to a minimum of $< 0.5 \mu\text{mol CO}_2 \cdot \text{cm}^{-2} \text{ TC SA} \cdot \text{s}^{-1}$ for the barrier and non-barrier plots, for both varieties 'Empire' and 'Liberty' and all treatments (Fig. 4 and 5). Environmental conditions on the dates that WPP was measured are given in Table 2.

Early in the season, there were greater differences between treatments than later in the season. In particular, for the first measurement period at petal fall, the two soft IPM treatments had higher rates of photosynthesis than the conventional IPM treatments and the control trees on the non-barrier plot 'Empire' and 'Liberty' (significant at $p \leq 0.10$), but was not significant for the barrier plot 'Empire' and 'Liberty' (Fig 4).

Total foliar damage due to insect feeding was estimated using the following formula: Total Damage index = number of mines + amount of feeding by lepidoptera + amount of damage causes by aphids + the amount of bronzing and burning. The non-barrier plot had more total foliar damage than the barrier plot in July, August and October (significant at $p \leq 0.05$) (Fig 6).

WPP decreased with increasing foliar damage (Fig. 7). Total foliar damage was found to be correlated with WPP on 'Empire' (Table 3) in July (significant at $p \leq 0.10$), August (significant at $p \leq 0.05$) and October (significant at $p \leq 0.05$) for non-barrier plot. Also, total foliar damage was correlated with WPP in August on 'Liberty' and 'Empire' (significant at $p \leq 0.10$) for both the

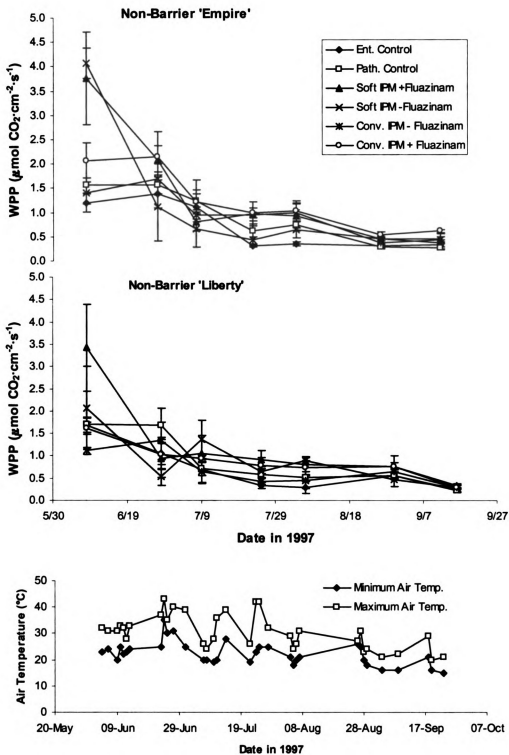


Figure 4. Whole plant photosynthesis per cm^2 TCSA measured during the 1997 growing season for non-barrier plot varieties 'Empire' and 'Liberty'. Vertical bars indicate standard error.

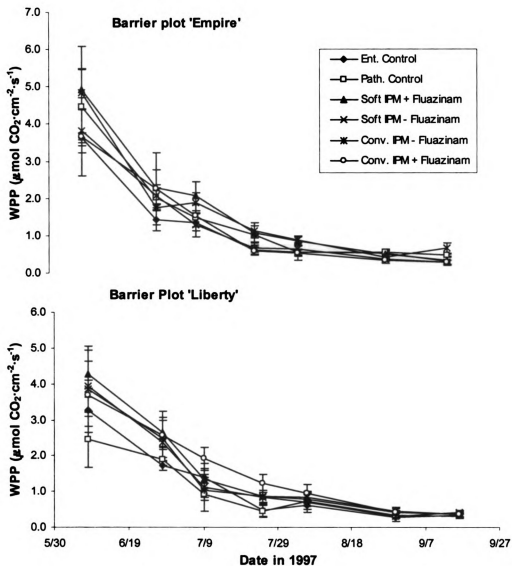


Figure 4 Continued. Barrier plot varieties 'Empire' and 'Liberty'.

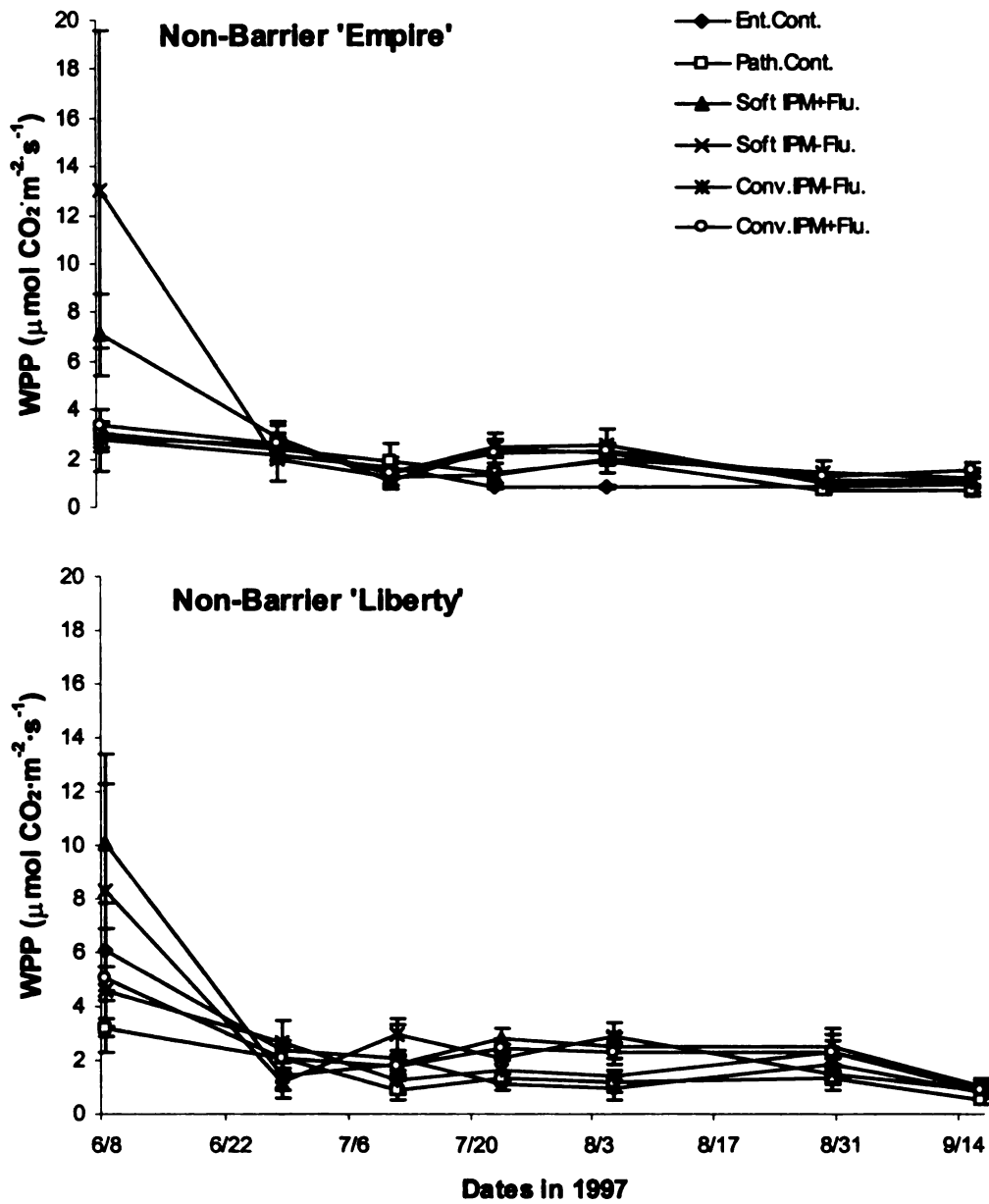


Figure 5. Whole plant photosynthesis per m^2 leaf area measured during the 1997 growing season for non-barrier plot varieties 'Empire' and 'Liberty'. Vertical bars indicate standard error.

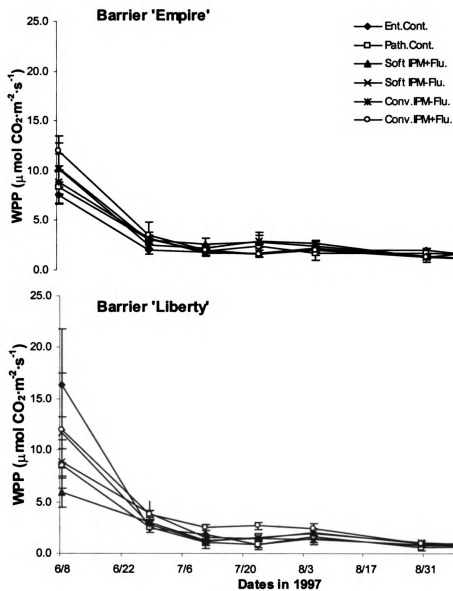


Figure 5 Continued. Barrier plot 'Empire' and 'Liberty'.

Table 2. Dates that whole plant photosynthesis was measured and the environmental conditions on those dates.

Growth Stage	Date	Air Temperature min.- max. (°C)	Light Conditions	weather station data	
				Air Temp. Max.	Total solar Rad. (ly/day)
Petal Fall	04-Jun	23-32	sunny	24.8	651.5
	06-Jun	24-31	sunny	23.4	321.2
	09-Jun	20-31	sunny	28.4	662.2
	10-Jun	25-33	sunny	33.2	681.4
	11-Jun	22-32	sunny	30.1	514.2
	12-Jun	23-28	sunny	24.8	562.3
	13-Jun	24-33	partly cloudy	28.7	570.3
Fruit size 18-22mm	23-Jun	25-37	sunny	30.9	513.3
	24-Jun	35-43	sunny	32.2	650.2
	25-Jun	30-35	sunny	28.3	620.3
	27-Jun	31-40	partly cloudy	29.2	724.7
	01-Jul	25-39	partly cloudy	29.1	518.9
Full Canopy	07-Jul	20-26	sunny	24.1	696
	08-Jul	20-24	sunny	23.2	205.1
	10-Jul	19-28	sunny	25.8	722.6
	11-Jul	20-36	sunny	27.7	689.8
	14-Jul	28-39	sunny	34.3	450.3
Full Canopy	22-Jul	19-26	sunny	25.7	462.2
	24-Jul	23-42	partly cloudy	29.4	470.9
	25-Jul	25-32	sunny	28.9	482
	28-Jul	25-32	sunny	31.1	647
Full Canopy	04-Aug	21-29	sunny	27.9	604.5
	05-Aug	18-24	sunny	24.8	651.6
	06-Aug	20-26	partly cloudy	25.9	476.9
	07-Aug	21-31	sunny	26.6	635
Full Canopy	26-Aug	26-27	sunny	24.8	415
	27-Aug	25-31	sunny	28.9	530.5
	28-Aug	20-23	partly cloudy	21.6	321.1
	29-Aug	18-24	partly cloudy	24.1	301.7
	03-Sep	16-21	sunny	21.4	569.9
Full Canopy	08-Sep	16-22	partly cloudy	20.5	361.2
	18-Sep	21-29	sunny	26.8	457.2
	19-Sep	16-20	sunny	25.4	62.4
	23-Sep	15-21	partly cloudy	20.9	387.8

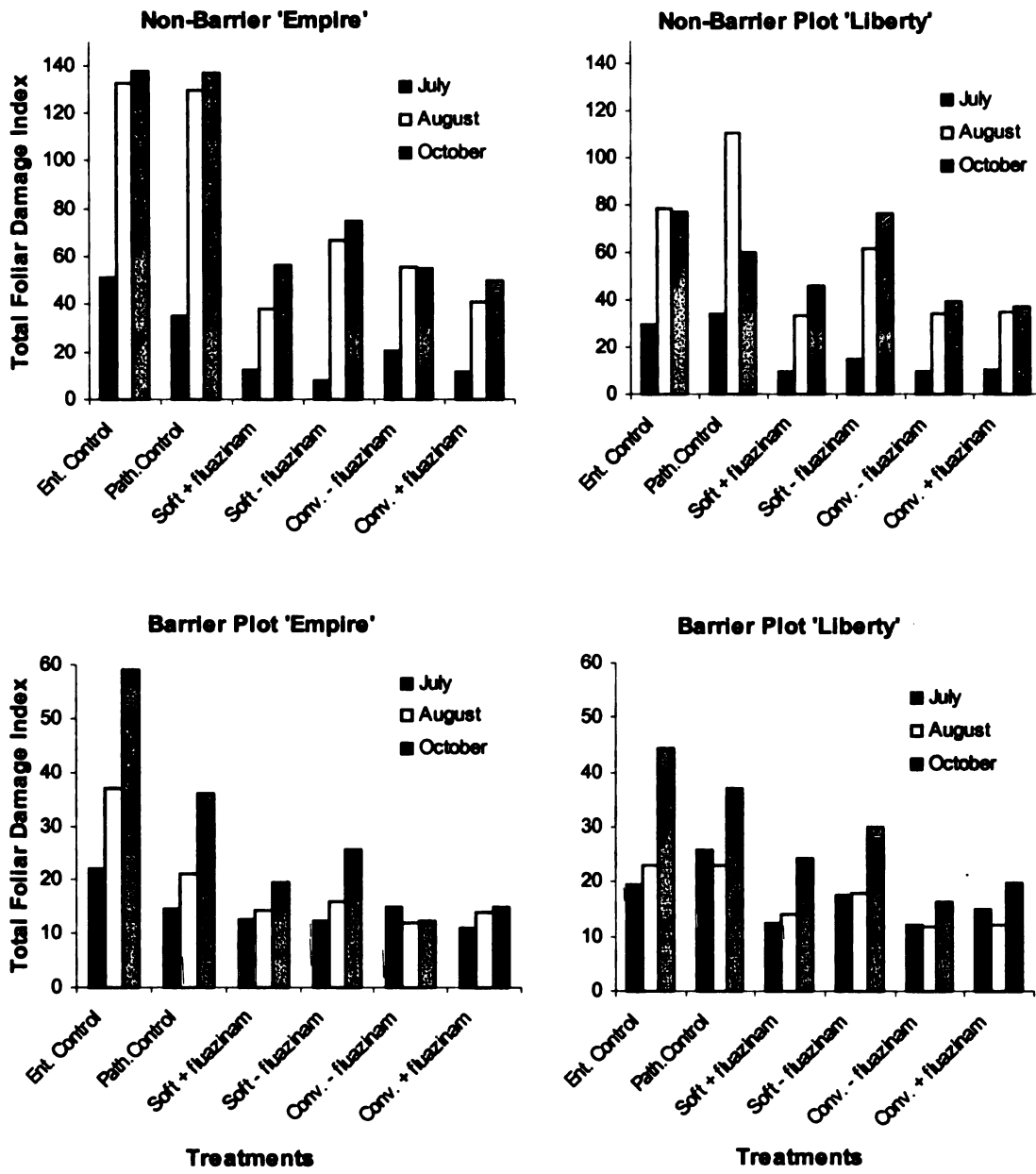


Figure 6. Total foliar damage for three dates in 1997 determined by the addition of individual damages from mines, lepidoptera, aphids and bronzing and burning.

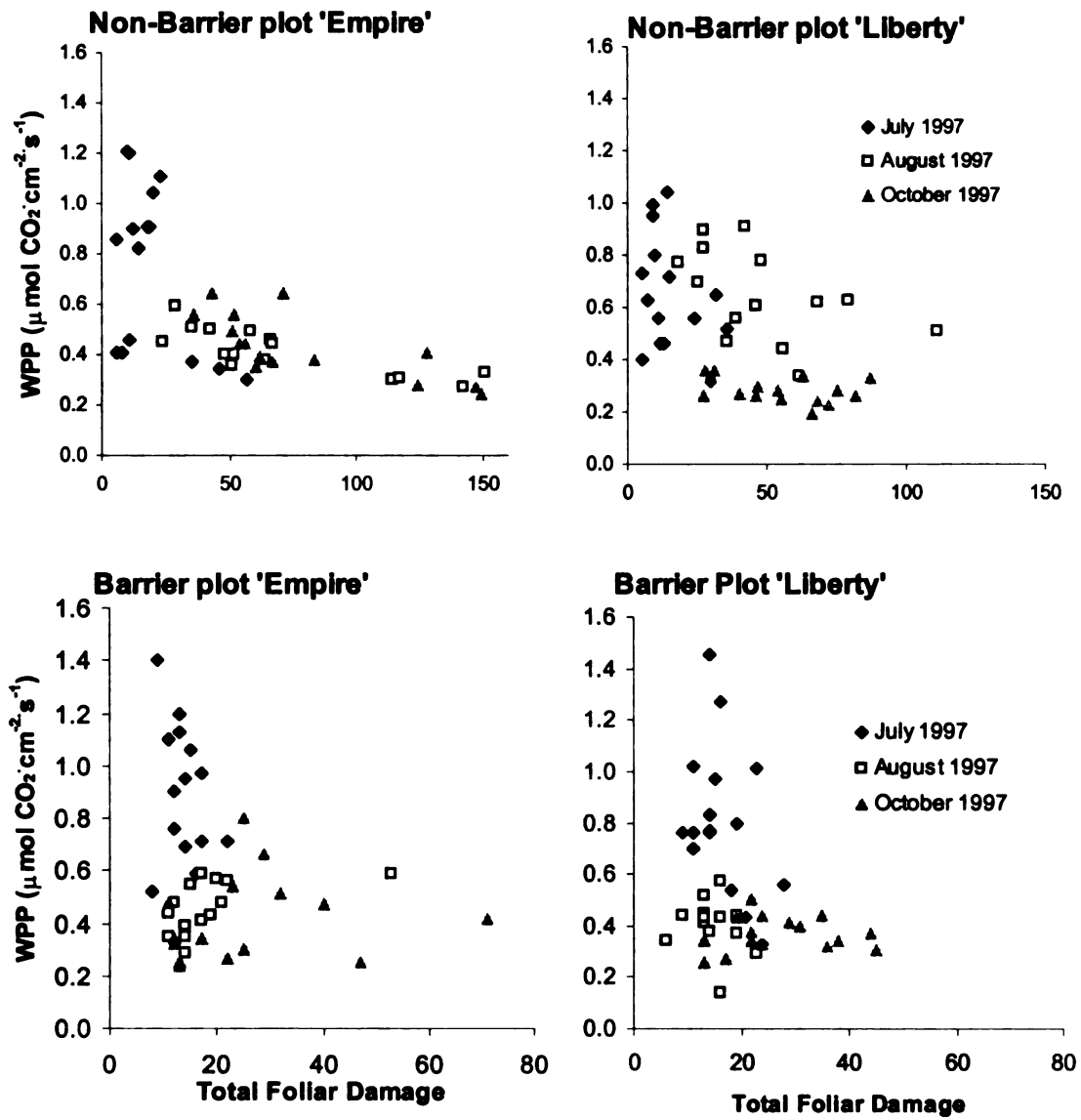


Figure 7. Foliar damage Vs whole plant photosynthesis for non-barrier and barrier plots varieties 'Empire' and 'Liberty'.

Table 3. Correlation between foliage damage and whole plant photosynthesis for 'Empire' and 'Liberty' apple using linear coefficient of determination (r^2), for IPM plots, CHES, 1997.

Damage Type and Date	Correlation between WPP and Damage (r^2)			
	Non-Barrier Empire	Non-Barrier Liberty	Barrier Empire	Barrier Liberty
Total Foliage Damage				
July	0.22*	0.11	0.08	0.15
Aug.	0.64**	0.25*	0.29*	0.07
Oct.	0.53**	0.14	0.02	0.00
Mines				
July	0.24*	0.06	0.10	0.05
Aug.	0.62**	0.26*	0.31*	0.18
Oct.	0.53**	0.13	0.02	0.00
Lepidoptera				
July	0.29*	0.03	0.10	0.16
Aug.	0.29*	0.00	0.00	0.00
Oct.	0.15	0.28*	0.01	0.01
Aphids				
July	0.05	0.03	0.00	0.01
Aug.	0.19	0.12	0.01	0.05
Oct.	0.11	0.11	0.00	0.22*
Bronzing and Burning				
July	0.00	0.27*	0.00	0.32*
Aug.	0.01	0.14	0.00	0.00
Oct.	0.25*	0.02	0.00	0.21*

$p \leq 0.10$ (*) and 0.05 (**)

barrier and non-barrier plots. Damage caused by tentiform leafminer was found to be correlated with WPP in July (significant at $p \leq 0.10$), August (significant at $p \leq 0.05$), and October (significant at $p \leq 0.05$) for non-barrier 'Empire' and in August (significant at $p \leq 0.10$) only for non-barrier 'Liberty' and barrier 'Empire' varieties. Damage caused by lepidoptera was found to be correlated with WPP in July and August (significant at $p \leq 0.10$) for non-barrier 'Empire' and in October (significant at $p < 0.10$) for non-barrier 'Liberty'. Foliar damage caused by aphids was found to be correlated with WPP in October (significant at $p \leq 0.10$) for barrier 'Liberty'. Bronzing and burning damage was correlated with WPP in October (significant at $p \leq 0.10$) for non-barrier 'Empire', July (significant at $p \leq 0.10$) for non-barrier 'Liberty', and July and October (significant at $p \leq 0.10$) for barrier 'Liberty'.

Average yield was greater in the barrier plot than the non-barrier plot (0.86 and 0.79 kg·cm⁻² TCSA respectively) (significant $p \leq 0.10$). Average yield for 'Empire' was higher than 'Liberty' (0.86 and 0.79 kg·cm⁻² TCSA respectively) (significant $p \leq 0.10$) (Table 4). Average fruit size was greater in the non-barrier plot than the barrier plot for both 'Empire' and 'Liberty' (Fig. 8). There were no yield differences between treatments. No significant correlation was found between total weight of fruit per tree and WPP (Fig. 9). A correlation was observed between total foliar damage and yield for the barrier 'Empire' in July, August and October (significant $p \leq 0.10$).

Table 4. a) Average yield per TCSA and % fruit > 130g for barrier and non-barrier plot and 'Empire' and 'Liberty'. b) Average yield per tree and % fruit > 130g for apple IPM plots, CHES, 1997.

a)	Average Yield (kg) per cm ² TCSA	% Fruit > 130g
Plot		
Barrier	0.86	39
Non-barrier	0.79	63
Variety		
'Empire'	0.86	46
'Liberty'	0.79	56

b)	Average tree yield (kg) per cm ² TCSA	% Fruit > 130g
Barrier plot 'Empire'		
Ent. Control	0.24	32
Path. Control	0.68	32
Soft IPM+Flu.	0.98	25
Soft IPM-Flu.	1.26	23
Conv. IPM-Flu.	0.68	29
Conv. IPM+Flu.	0.76	42
Barrier plot 'Liberty'		
Ent. Control	1.06	34
Path. Control	0.80	54
Soft IPM+Flu.	0.90	63
Soft IPM-Flu.	0.88	34
Conv. IPM-Flu.	0.87	41
Conv. IPM+Flu.	0.95	55
Non-barrier plot 'Empire'		
Ent. Control	0.91	52
Path. Control	0.85	57
Soft IPM+Flu.	0.94	68
Soft IPM-Flu.	0.98	61
Conv. IPM-Flu.	0.89	58
Conv. IPM+Flu.	0.89	79
Non-barrier plot 'Liberty'		
Ent. Control	0.66	50
Path. Control	0.63	74
Soft IPM+Flu.	0.78	70
Soft IPM-Flu.	0.87	38
Conv. IPM-Flu.	0.53	76
Conv. IPM+Flu.	0.57	76

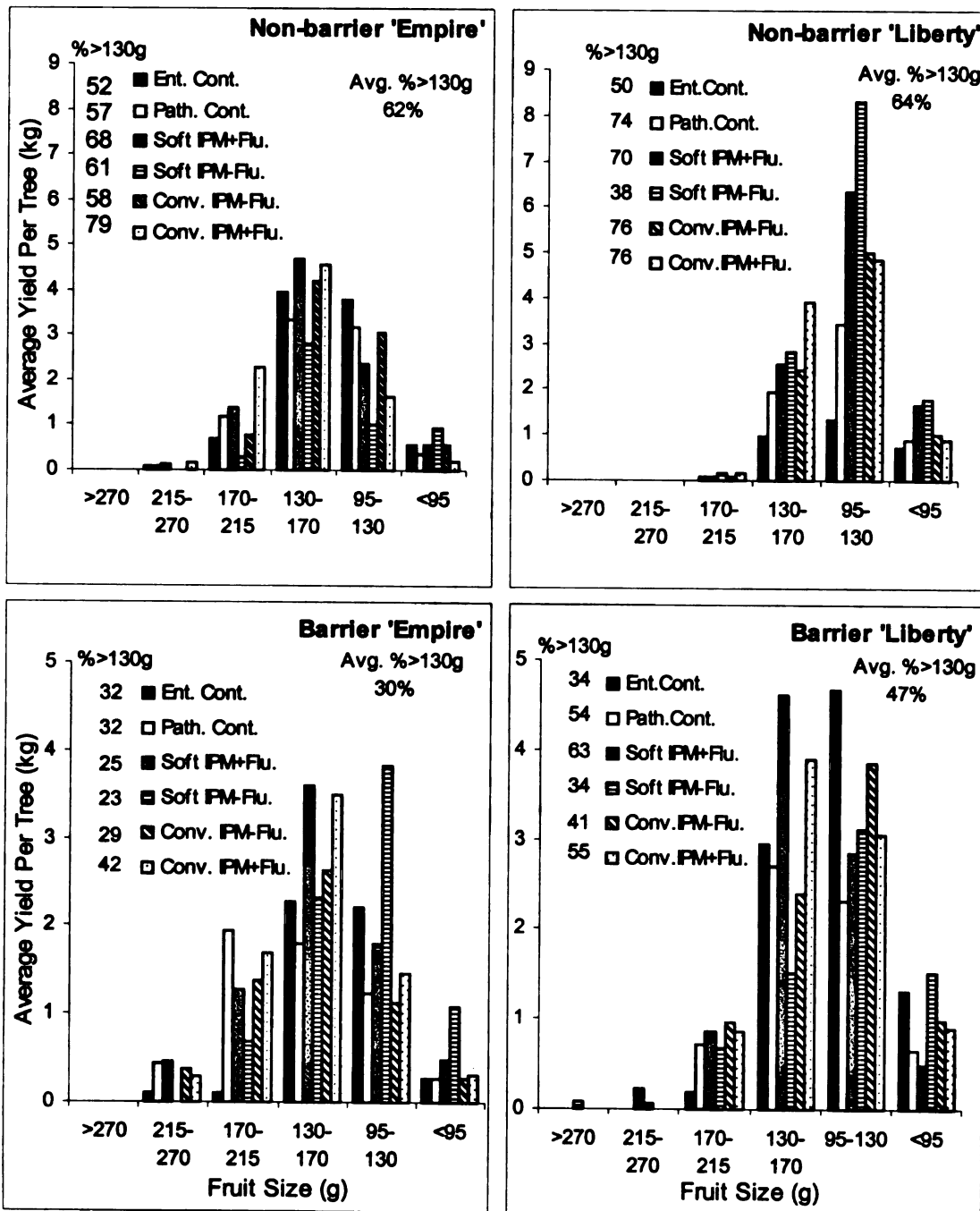


Figure 8. Fruit size Vs average yield per tree for non-barrier and barrier plots varieties 'Empire' and 'Liberty' for 1997.

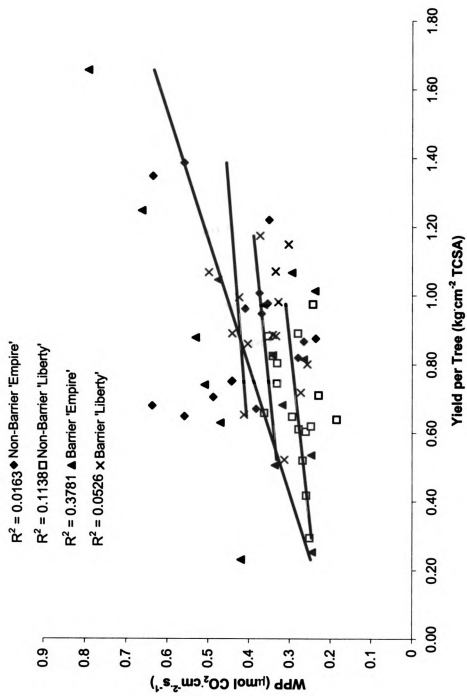


Figure 9. Yield per tree per TCSA and whole plant photosynthesis for non-barrier and barrier plots, varieties 'Empire' and 'Liberty', CHES, 1997.

1999 Potted Plant Experiment.

WPP of the soft IPM treatment (Elite[®], Dithane[®] Provado[®] and Spintor[®]) were found to be slightly greater than the conventional IPM treatment (Dithane[®], Lorsban[®] and Lannate[®]) and the control (no pesticides) on all three dates of measurement (Table 5). In addition, we found that the soft IPM treatment had higher rates of single leaf photosynthesis than the conventional IPM and the control for the first, second, and fourth dates of measurement (June 17, June 21 and July 12, 1999 respectively) (Table 5). On the third date (June 28, 1999), the single leaf photosynthesis of the conventional IPM treatment was greater than the soft IPM and control treatments. Measurements of average shoot number and length showed no differences between treatments (Table 5).

Table 5 a) Whole plant photosynthesis for potted apple trees. b) Single leaf photosynthesis for potted apple trees. c) Shoot number and average shoot length for potted apple trees. Means for each date followed by the same letter are not significantly different (Duncan's test $p \leq 0.10$).

a)		Average WPP	
Treatment	Date	$\mu\text{mol CO}_2 \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$	
	17-Jun		
Control		0.39	a
Conv. IPM		0.51	ab
Soft IPM		0.55	b
	18-Jun		
Control		0.42	a
Conv. IPM		0.62	a
Soft IPM		0.55	a
	25-Jun		
Control		0.60	a
Conv. IPM		0.71	ab
Soft IPM		0.80	b

b)		Single leaf Pn	
Treatment	Date	$\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	
	17-Jun		
Control		6.68	a
Conv. IPM		6.28	ab
Soft IPM		7.74	b
	21-Jun		
Control		5.66	a
Conv. IPM		7.05	b
Soft IPM		8.70	c
	28-Jun		
Control		8.52	a
Conv. IPM		10.84	a
Soft IPM		10.24	b
	12-Jul		
Control		8.14	a
Conv. IPM		7.83	a
Soft IPM		8.17	a

c)		Avg. Shoot Length	
Treatment	Average Shoot number	per tree (cm)	
Control	14.3a	32.72a	
Conv. IPM	14.6a	32.69a	
Soft IPM	13.8a	30.89a	

Discussion

In our research we attempted to develop a damage threshold for foliar pests in apple through the use of WPP. A correlation was found for total foliar damage and WPP in the non-barrier plot for all three assessment dates in 'Empire' and August only in 'Liberty'. The correlation between WPP and damage could be interpreted that a damage threshold was reached in the non-barrier plot, where there was greater foliar damage, whereas, in the barrier plot, where there was much less damage, no threshold was reached. We observed more correlations between WPP and total foliar damage for 'Empire' than 'Liberty'. 'Liberty' was developed as a disease resistant variety, which in experiments has produced excellent quality fruit with no fungicide sprays (Ellis, et al., 1994). Possibly 'Liberty' is more resistant to insect feeding than 'Empire' as well.

Damage caused by tentiform leafminer was also found to be correlated with WPP for non-barrier 'Empire' on all three assessment dates and in August for non-barrier 'Liberty'. This was the only individual insect damage that was correlated to WPP. Possibly damage done by leafminer is much more influential in reducing WPP than the other individual pests. Kappel et al. (1987) reported increased ethylene levels of leaves damaged by spotted tentiform leafminer which can lead to premature fruit and leaf drop.

Yield was not found to be correlated with WPP. This is not an uncommon result as reduction in photosynthetic capacity does not always culminate in reduced yield. Results of studies have varied considerably, probably due to differences in the environment, the timing and severity of the damage and the

physiological status of the tree, especially crop load (Francesconi et al., 1996a). Yield was greater in the barrier plot than the non-barrier plot. Possibly due to the reduced amount of foliar damage that the barrier plots experienced. The non-barrier trees could have had reductions in production of photosynthates caused by reduction in leaf area by insect feeding. One reason for this difference could be because of the barrier surrounding the plot. There was less wind movement within the barrier plot which may have reduced some damage to the trees and crop and reduced water loss (Solomon, 1981). The yield in the non-barrier plot may also have been reduced by the foliar damage that occurred. Disegna (1994) showed that inhibition of photosynthesis at 15 and 30 DAFB reduced the yield indicating that timing of damage is very important. Lakso et al. (1998) demonstrated that just after bloom and just before harvest are two periods where damage to leaf area could affect yield. These are two periods when carbohydrates could be limiting.

We observed a decline in photosynthesis as the season progressed. There are many variables that can affect photosynthesis. In general leaf photosynthesis peaks just before the leaf reaches full expansion, remains steady for some time, then decreases (Flore and Lakso, 1989). The rate of decline can be slowed with the presence of fruit (Downtown et al., 1987), by debudding (Satoh et al. 1977) or by summer pruning (Rom and Ferree, 1985). For example seasonal effects have been shown for apple where maximum assimilation rates were observed in late June when leaves reached full expansion then declined to a minimum at the end of July (Ghosh, 1973). Cherry leaves were shown to reach

their maximum rate of photosynthesis at 80% leaf expansion and remain at a maximum level for 2-4 weeks before declining (Sams and Flore, 1982).

Another important factor in photosynthesis is light intensity, but likely it was not a factor for the decline in photosynthesis as the season progressed because all the measurements were determined under saturating light intensities, which for apple are 400-600 $\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for individual apple leaves (Faust, 1989).

Air temperature is another possible factor for the decline in WPP over the season. High air temperatures can increase respiration rates and cause an apparent drop in the rate of photosynthesis (Heinicke and Childers, 1937). The air temperature for optimum photosynthetic rate of apple leaves is between 20 and 30°C above which photosynthesis declines (Lakso and Seeley, 1978). For potted plants this temperature is even lower. Apple leaves showed decreases in photosynthesis above 20°C and appeared to be very sensitive to increases in vapor pressure deficit compared to other species (Higgins et al., 1992). More recent studies on whole plants have demonstrated small decreases in photosynthesis above 15°C, and drastic declines above 25°C indicating that the optimum temperature for WPP is much lower than previously thought (Francesconi et al., 1998). Stomata are involved in the regulation of CO₂ exchange and water vapor diffusion. Transpiration is induced by evaporative demand and is driven by temperature and humidity. In the case of high temperature and low relative humidity large differences in water vapor concentrations between the leaf surface and the air can occur and cause closure of stomata.

Crop load can have an effect on the rate of photosynthesis as well. While it appears that crop load affects the vegetative-reproductive ratio, its effect on photosynthesis is not well known. Giuliani et al. (1997a) observed differences in photosynthesis with fruiting and non-fruiting trees, but did not detect a difference between crop loads. Another study with apple showed that after canopy development, there are higher rates of photosynthesis in fruiting trees than non-fruiting trees during the period of rapid increase in fruit growth (Fujii and Kennedy, 1985). Ghosh (1973) found that towards the end of the vegetative period the leaves of fruit-bearing shoots showed a slightly higher rate of photosynthesis, whereas, leaves of shoots without fruits showed a reverse trend. The time of photosynthesis measurement is important with relation to crop load. In grape vines, during the period of rapid sugar accumulation by the fruit, photosynthesis of plants with and without fruit were similar early in the day, but declined earlier in the day for the non-fruiting vine. The difference in photosynthesis between the fruiting and non-fruiting vines may have resulted from carbohydrates building up faster in the non-fruiting vine resulting in feedback inhibition (Downton et al., 1987). In orchard studies, Kennedy and Fuji (1986) observed two periods during the growing season when the rate of photosynthesis in leaves of fruiting spurs was 10-20% higher than the leaves on non-fruiting spurs. The first period was during flowering, and the second during fruit maturation. For 2-4 weeks after bloom, fruits are supported mainly by carbohydrates from spur leaves and growing shoots receive most of their carbohydrates from extension leaves on the shoot (Lakso et al., 1997). During

this 2-4 week period, and just before harvest appear to be two periods during the growing season that are possible potentials for carbon limitation for apple fruit growth (Lakso et al., 1998). Meaning that damage occurring in these periods could have more of an impact on yield than other periods. If crop load is high there will be more of an effect than if crop load is light (Francesconi et al., 1996b).

Injury to the leaf caused by diseases or insects, as well as defoliation, has the potential to decrease photosynthesis rate and cause economic loss. Outbreaks of mites in an orchard can reduce the rate of photosynthesis significantly. Ferree et al. (1986) found that as the population of two-spotted spider mites (*Tetranychus urticae*) increased, photosynthesis decreased and the reductions appeared to permanently destroy the photosynthetic capacity of the leaf. A population of 60 mites per leaf caused a significant reduction in apple photosynthesis three days after placement on the leaf. Nine days after infection, 15 mites per leaf reduced photosynthesis by 26%, 30 mites per leaf by 30%, and 60 mites per leaf by 43% below the value observed in uninfected controls. Foliar damage causes reductions in the ability of leaves to make sugars by photosynthesis. This reduces the amount of carbohydrates that are translocated to the fruit which can cause reductions in fruit size and quality. Damage caused by European red mite can cause fruit growth reductions earlier and more severe on normally cropped trees than on lightly cropped trees (Francesconi et al., 1996b). In a previous study Lakso et al. (1996) introduced the term mite days

which are the previous number of mites per leaf added to the current number of mites per leaf and multiplied by the number of days between samples.

The reductions in WPP that we saw throughout the season could be due to any one or a combination of the factors above. The trees in the non-barrier plot had a lower rates of WPP than those in the barrier plot. There was also more damage in the non-barrier plot than the barrier plot both by insects and possibly by other factors such as diseases and wind. The yield in the non-barrier plot was less than that of the barrier plot suggesting that there could be an effect from the increased damage experienced in the non-barrier plot, even though yield was not found to be correlated with WPP.

Early in the season, there were greater differences between treatments than later in the season. In particular, at the beginning of the season, the two soft IPM treatments had higher rates of photosynthesis than the conventional IPM treatments and the control trees. This was the case for both the non-barrier and barrier plots and both varieties 'Empire' and 'Liberty'. We repeated this experiment on potted plants in 1999 and found results to be consistent with the 1997 field study. One explanation for the increase in photosynthesis that the soft IPM treatments showed could be due to the pesticides themselves. The two insecticides used were Provado[®] and Spinosad[®]. Provado[®] is an insecticide used at petal fall to prevent leafminers, rosy apple aphids, and leafhopper. It's active ingredient is imidacloprid which is a systemic, chloro-nicotinyl insecticide. It works by interfering with the transmission of stimuli in the insect's nervous system. Specifically it causes a blockage in a type of neuronal pathway that is

more abundant in insects than warm-blooded animals. This blockage leads to accumulation of acetyl choline, an important neural transmitter, resulting in the insect's paralysis and eventual death (The pesticide management education program, 1999). Spintor[®] controls lepidoptera larvae, leafminers and thrips. It is a fermentation product derived from tetracyclic macrolide produced by the actinomycete, *Saccharopolyspora spinosa* and consists of two structurally related compounds, namely spinosyn A and spinosyn D which provide the insect control activity. In addition to the two pesticides used, two fungicides were applied namely Dithane[®] and Elite[®]. Dithane[®] is a broad-spectrum, fungicide. Its active ingredient is Mancozeb which belongs to the chemical family ethylene bisdithiocarbamates (EBCDs). It controls fabrea leaf spot, rusts and scab (The pesticide management education program, 1999). Elite[®] controls powdery mildew and leaf spot. Its active ingredient is Tebuconazole which is a sterol demethylation inhibitor (DMI) fungicide. It is systemic and provides control by preventing completion of the infection process. It is rapidly absorbed by plants and is translocated in young growing tissues (The pesticide management education program, 1999).

Because some of these chemicals have effects on metabolic pathways in insects, perhaps these chemicals may cause metabolic changes in plants as well. In addition, there have been studies showing that pesticides with different modes of action can have synergistic effects which can be either positive or negative. Samoucha and Gisi (1986) found that mancozeb mixed with metalaxyl provided better control of downy mildew than either of the chemicals alone. In a

study with tebuconazole (the active ingredient in Elite[®]), rape was found to have higher yields with the use of tebuconazole as compared with two other fungicides (Kaspers and Siebert, 1989). Catrso et al. (1997) also found tebuconazole to have an effect other than its fungicide properties. They found that it increased the number of sprouts established in citrus. There is some evidence pointing to seasonal variation in spray retention by leaves of apple (Hall et al., 1997). Spray retention was found to correlate positively with root hair density. This could potentially be a reason for the positive effect of the pesticides on WPP that we observed at the beginning of the season. Young leaves have many more trichomes than older leaves and, therefore, retain the spray longer.

Summary and Conclusions

The use of WPP as a possible tool to determine damage thresholds has been demonstrated. If carbohydrate supply and demand is the mechanism by which various foliar feeders affect apple tree productivity, then we can attempt to understand the amount of damage that can occur before the need for some type of action. This is especially helpful with our knowledge of times during the growing season that are particularly sensitive to decreases in photosynthesis and the interaction with crop load.

Although our results in general support our hypothesis and are promising, further research should extend to different damage levels to more fully define the interactions between WPP and damage.

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