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A linear programming model and partial budget analysis to optimize management strategies of western flower thrips in greenhouse impatiens production

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A LINEAR PROGRAMMING MODEL AND PARTIAL BUDGET ANALYSIS TO OPTIMIZE MANAGEMENT STRATEGIES OF WESTERN FLOWER THRIPS IN GREENHOUSE IMPATIENS PRODUCTION

A Thesis

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in

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by
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Table of Contents

Abstract

The research problem of this thesis was to compare strategies and costs of protecting impatiens in greenhouse culture from western flower thrips that would provide a plant of acceptable quality to the market and would address the issue of development of resistance to commonly used pesticides by evaluating biopesticides. Partial budgets based on alternative strategies were identified. Six control strategies were identified from a combination of commercial growers, research experts and biopesticide recommendations from product distributors. The research-recommended strategy 6 had the highest total production cost ($197.44), while one of the grower strategies based on conventional pesticides had the lowest total cost ($153.28). The second growers' strategy had the second lowest total cost by relying on scouting and pesticide application as needed. This strategy used the smallest quantity of pesticides, and was expected to reduce or prevent resistance and minimize environmental impacts. Biopesticides had higher prices than conventional pesticides. Three biopesticide recommendation strategies (3, 4 and 5) were in the midrange of production cost. The treatments containing biopesticides usually had higher product and production cost than treatments that included only nonbiopesticides.

An integer linear programming model was developed to determine the optimal WFT control program for impatiens. Constraints included pesticide mortality and label limits on consecutive or total applications per crop cycle. All pesticides in the linear programming solution were conventional. Biopesticides were not included in the solution because mortalities of biopesticides were far below the threshold, according to research reported through the IR4 program. The costs of using pesticides include economic product costs and environmental costs.

Using biopesticides to replace conventional pesticides in a rotation scheme of conventional ones with different modes of action could reduce water and soil pollution while maintaining crop quality.

Chapter 1. Introduction

1.1 Introduction

The ornamental horticulture industry consists of floriculture (including cultivation of foliage and flowering plants often grown in greenhouses), and nursery crops (usually woody perennial plants grown in open areas) (USDA, 2007). Horticulture has been one of the fastest growing agricultural sectors over the past decade and contributes significantly to the agricultural output of the U.S. (USDA, 2007). According to the 2002 Census of Agriculture, total sales of greenhouse and nursery crops from all 50 states were about $15 billion in 2002, had reached $16 billion by 2005, and were reported to be $17 billion in 2007 (USDA, 2002; USDA, 2007). The outlook for the horticulture industry is promising.

Ornamental plant production in Louisiana has experienced little growth in the past three to five years. The wholesale value of nursery-grown ornament production in Louisiana was around $120 million. Floriculture/bedding plants accounts for about 30 percent of Louisiana's nursery crop production in 2008 (LSU AgCenter, 2009).

Though the horticulture industry continues to grow, insect pests are a challenge which could constraint its development. Pests have caused huge damages to ornamental greenhouse crops that have been subjected to physical or aesthetic loss. Thrips are common pests of greenhouse plants and crops. There are around 6000 different species of thrips (Cloyd, 2009). The western flower thrips (WFT), *Frankliniella occidentalis*, is one of the most serious pests of ornamental crops as well as many other crops throughout the world (Lewis, 1997). It is also reported as one of the top three thrips having serious impact on floricultural protected crops (IR-4 Ornamental Horticulture Survey, 2007). WFT was first reported in 1895 (Driesche, 2010). In the 1970s and early 1980s, WFT spread throughout North America. Soon it was found in Europe and Dutch greenhouses. Since then it has become an exotic pest of greenhouse production in many countries throughout the world due to the global trade in horticultural products (Frantz and Mellinger, 2009). WFT is now established throughout North America and many countries of Europe, Asia, South America, Africa, and Australia (Kirk and Terry, 2003).

WFT is a significant pest of almost all crops, including fruiting vegetables, leafy vegetables, ornamentals, tree fruits, small fruits, and cotton (Lewis, 1997). It could cause a wide range of crop damage due to its inherent excessive feeding (Lewis 1997). It primarily feeds on young tissue in the bud or on newly expanded leaves by sucking up sap, thus causing considerable aesthetic damage to ornamental and fruiting crops (Cloyd, 2009). The direct symptoms of WFT feeding include surface blemishes formed at the oviposition site, distorted growth, sunken tissues on leaf undersides, and deformation of flowers (Van Dijken, 1994). Further, pathogens such as fungi can easily enter plants through the feeding wounds created by WFT and do more harm to crops (Cloyd, 2009). In addition, WFT can transmit plant viruses to some crops; the most severe two are tomato spotted wilt virus and impatiens necrotic spot wilt virus (Terry, 2010).

WFT is a damaging pest and virus vector on both outdoor crops and in greenhouse vegetable and flower crops (Robb and Parrella, 1989). There is not much information about total economic loss since some indirect loss is hard to evaluate. Nuessly and Nagata (1995) reported that losses caused by F. Occidentalis and Thrips Palmi (the most serious pest of a number of glasshouse and field crops in southern states) in 1993 in Florida exceeded $10 million. Zhang et al. (2007) reported annual losses of up to $75,000 per hectare caused by direct damage to cucumbers in a UK glasshouse. The indirect damage was even more serious. Thousands or millions of dollars worth of crops may have been destroyed by tomato spotted wilt virus (TSWV) and impatiens necrotic spot virus (INSV) (Lewis, 1997). Hausbeck et al. (1992) reported that an infection by TSWV and INSW virus caused $675,000 in losses in Pennsylvania in 1990.

By far the greatest damage caused by WFT is its ability to transmit *Tospoviruses.* WFT is known to be the primary vector of TSWV and INSV which occur in the U.S. (Driesche, 2010). As an accurate value of loss is difficult to obtain, an estimate that TSWV alone causes over $1 billion in losses annually to various crops has been reported (Goldbach and Peters, 1994). WFT is the only thrips species that can transmit INSV (Cloyd, 2009). INSV is becoming one of the most important problems in the floriculture industry today. This virus is widespread due to the distribution of infected plant material and the extensive spread of WFT which transmits the disease. INSV causes significant losses on a great variety of glasshouse ornamentals in many countries (Wick, 2009). The type of damage and loss caused is more or less the same as that caused by TSWV (Wick, 2009).

Impatiens is a native plant which can grow throughout moist forests in eastern North America (Schemske, 1978). It is one of the most popular of warm-season bedding plants in the U.S. Based on USDA's survey data, the wholesale value of impatiens in the U.S. was around $153 million in 2008 (USDA, NASS, 2008). WFT is the primary pest on impatiens (Casey, 1997). Impatiens growing under greenhouse conditions is prone to attack by WFT. The populations of WFT have been shown to grow rapidly in the presence of impatiens flowers (Gerin et al., 1999). Many species of thrips feed on nutrients from plant pollen (Ugine et al., 2006a). Adult female WFT reared on impatiens foliage supplemented with impatiens pollen produced 2-3 times more offspring per day compared to females provided only with impatiens foliage (Ugine et al., 2006a).

Given the documentation of the seriousness of the WFT, *Frankliniella occidentalis* as a pest of ornamental crops, as well as many other crops throughout the world (Lewis, 1997), a proposal to study the problem of resistance to spinosad was developed and funded by the Special Research Grants Program – Pest Management Alternatives, Plant and animal Systems Unit, CSREES/USDA for the years 2010 and 2011. Some experts from the approved grant proposal described the horticultural and economic situation and objectives.

As reported in the Annual Ornamental Research Priority Survey Summary conducted by the USDA Inter-Regional Project 4 (IR-4), thrips (mainly WFT) has been ranked in the top three arthropod pests (with two spotted spider mite and aphids) for three consecutive years from 2006 to 2008, nationally and in the Southern Region (IR-4 Ornamental Research Priority Summary, 2008).

The proposed alternative thrips management strategy consists of two components. The first line of defense against thrips is cultural practice, namely manipulating nitrogen (N) and phosphorous (P) and using a resistant cultivar to help reduce pest damage and outbreak. Two biopesticides (QRD 452 and Met 52) that may provide satisfactory control on nymphal and adult thrips will be the second line of defense and part of a resistance management program for Conserve which is currently commonly used to control WFT.

1.2. Problem Statement

Pesticides are a common pest management strategy. Traditionally, chemical pesticides have been the most used and most effective way to control pests in crops. However, overuse of pesticides in agriculture has resulted in insect resistance and environmental pollution problems (Kos et al., 2009).

As we know, sustained use, abuse usage and overuse of pesticides can result in high resistance of insect to pesticides (Cloyd, 2009). Some insecticides, such as spinosad, which were effective in controlling pests at the beginning, have been documented to be ineffective on pests after many years' application. New pesticides must be developed which increase production cost and environmental hazard. Spinosad, trade name Conserve, has been an effective pesticide since it was developed in 1985 (Nayak et al., 2005). Due to its high efficacy for thrips control, spinosad had become almost the only insecticide used against thrips in some areas. Some growers havw applied more than 10 applications of spinosad on crops per growing cycle (Bielza et al., 2007). The high application rates led to thrips resistance. Loughner et al. (2005) reported thrips were resistant to spinosad when spinosad was applied up to 8 times a year. Thus, it is essential to reduce the use of spinosad or replace spinosad with alternatives to prevent the spinosad resistant thrips in greenhouse production.

Biopesticides have several advantages over chemical pesticides. First, since biopestcides come from plants or microbes, their composition is usually inherently less toxic than conventional pesticides. They are chosen to affect only the target pest and closely related organisms, while conventional pesticides may affect pests as well as organisms, birds, insects, and mammals. Biopesticides' compositions are usually effective at low levels and they decompose quickly, resulting in lower exposures and largely avoiding the pollution problems caused by conventional pesticides (Kogel et al., 2004b). Besides biopesticides, genetic modifying technology is another method to avoid the insect resistance problem. This technology has provided new developments such as resistant cultivar which is an environmentally friendly pest control technique. Researchers are doing more experiments in this field.

Problems with control of WFT in production of impatiens include direct and cross resistance to commonly used insecticides. Since WFT has high a reproductive rate, has a short-term egg to adult life cycle, prefers cryptic habitats, and is resistant to insecticides, sustained pesticide use may lead to resistance within insect populations (Zepeda et al., 2006). An effective way to control WFT in the greenhouse is needed.

Usually, there are four ways to reduce resistance: (1) reducing pesticide use, (2) using biopesticides to replace conventional ones, (3) using newly developed pesticides, and (4) using rotation programs with different modes of action. Development of new pesticides is expensive. It takes an average of 9.8 years between the first research tests and registration of a product (Whitford et al., 2006). It was reported that the average cost of developing a new pesticide was about $80 million (Muir, 2012). The cost would be transferred from the buyer to the seller, and finally these costs would be shifted to the users in the industry. The total amount of pesticides used has increased during the past several years (EPA, 2011). The benefits of appropriate use of pesticides to the costs of inappropriate use of pesticides were about 20 to 1 (Crop protection, 2010). Based on these producers' needs, investment in research is needed to determine appropriate WFT processes in greenhouse production.

A separate set of problems related to economic issues in pest management as related to efficacy and cost has not been addressed in sufficient detail. Generally, field experiments have focused on problems within specific disciplines. Therefore, greenhouse producers have been offered suggestions for problems relating to crop production, for example, which cultivar is a good selection, how much fertilizer should be applied, what are the optimum pesticide rates, and timing, etc. Many practitioners have found that a single solution in pest management is rarely sufficient and usually has short duration (Kos et al., 2009). Thus, other pest management strategies must be implemented or considered in conjunction. Since factors such as pesticides, fertilizers and cultivars could affect the yield and quality of the product, it is important for growers to incorporate low cost and high efficacy production factors into pest management programs for greenhouse impatiens production to compete in the market. No previous study has investigated the integration of alternative tactics and WFT management on impatiens production in a greenhouse.

Growers' motivations and incentives encourage them to produce high quality crops with biodiversity. The market demand is important to ornamental crops' production because consumers usually prefer new, improved, easy-to-grow and unusual plant varieties or cultivars. In order to satisfy this demand, horticulturists evaluate seedlings or select cultivars with specific characteristics, such as plant size, shape, flower color and disease resistance (Bethke and Cloyd, 2009). Farmers face a decision about how to allocate their production resources based on their previous experience and the existing farm plan. In order to maintain a successful business, producers must consider production cost to ensure a return on their investment.

Like Jetter (2005) indicated, it was a challenge to assess all benefits and costs to a pest control program due to the different approaches and dynamic factors. In addition, few economic feasibility studies have been conducted on horticultural pest management (Olson et al., 1996). An economic model is needed for growers to estimate costs and benefits of WFT control on greenhouse impatiens production.

A set of experiments was conducted to answer questions of science regarding the relationship between production quality and quantity. In these experiments, biopesticides in conjunction with conventional pesticides were evaluated for their possible contribution to control WFT. The absence of studies of economic feasibility of the different production factors and their relationship to pest management strategy affects the efficiency and effectiveness of producers' decisions in terms of profitability and of slowing WFT resistance to conventional pesticides (Eigenbrode and Trumble, 1994).

1.3 Justification

There are significant socio-economic as well as environmental benefits to be gained from this research. The study will deliver substantial economic information to the whole greenhouse impatiens industry. Benefits of cultivars, pesticides and nutrient management could increase crops yields and reduce production costs. As we know, if the optimum choice of the three production factors is used, farmers may not only reduce the impatiens greenhouse production cost and increase its benefits, but also reduce the amount of pesticides and nutrients. Thus it could reduce the environmental chemical hazard caused by pesticide application to crops, prevent or reduce water pollution from over-fertilization, and maintain the soil's water holding capability, etc. This information could help impatiens growers control pests, maximize impatiens market returns and meanwhile protect the environment.

1.4 Objective

The objective of this study was to provide an analysis of alternative schemes of WFT control that were designed to reduce production costs and reduce pesticide use in greenhouse production of impatiens. The subpurposes of this study were to evaluate the following factors on cost and profitability:

(a) To identify thrips control options for impatiens (alternative impatiens WFT control programs, including biopesticides used alone, in combination, and conventional products alone) and to estimate the production cost of each scheme.

(b) To determine optimal thrips control programs using linear programming procedures.

The content of this study was mainly focused on how to obtain an optimized pesticide application scheme which had lower total production cost and had higher WFT control efficacy in greenhouse impatiens production. Chapter 1 gave a background introduction to the project, identified the problem and stated the objectives of this study. Chapter 2 reports the related research results and the methods researchers have used in the literature review. The total production cost for each strategy by using partial budget analysis method is calculated in Chapter 3. A linear programming model aimed to optimize the pesticide program is constructed and the optimal pesticide scheme was interpreted in chapter 4. Chapter 5 is a results summary section.

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Chapter 2. Literature Review

2.1 Introduction

Literature in economics was reviewed for analysis of outcomes of individual activities and pest management strategies. There has been a significant amount of analysis of efficacy of alternative treatments in the area of controlling of weeds, insects and other pests. However, those experimental strategies and outcomes have received relatively little economic analysis. This extends to experiments evaluating strategies for control of various insect pests on impatiens. In this section, reports from studies that relate directly to management of western flower thrips (WFT) on impatiens, and more generally to management of insect pests on crops, is presented under topics of cultivar effects, nutrition effects, and pesticide efficacy.

To satisfy the rising demand for ornamental plants and greenhouse crops, growers are interested in producing large numbers of high quality crops. To maximize returns in an increasingly competitive market, farmers must determine the most cost effective production method. A producer would make a decision to remain in production in the short run if marginal revenue is equal to or greater than marginal cost (Pindyck and Rubinfeld, 2001)..

2.1.1 Research on pesticide use

The principal management strategy to control pests is to use insecticides. Hundreds of pesticides have been developed and used in horticulture (Cloyd, 2009). The same approach has been used in WFT control. However, most of the pesticides are useful when WFT is in its initial life stage and its population is low. Also, some of them only kill the nymphs or adults of WFT with no activity on the egg or pupae stage (Seaton et al., 1997). What is more, applying more repetitions of insecticides means more effective and higher volumes of insecticides are needed to kill WFT because at any time they are in different life stages and hide in areas of plants such as unopened flower buds and inner leaves of plants that are hard to reach with pesticides (Lewis, 1997). Due to the problems of developing pest resistance, short term duration (opposite of long-term duration, usually indicates short time period effectiveness of pesticides), the damage caused to non-target organisms and the environmental hazards of chemical insecticides, there is increasing interest in biological control pest on crops (Moazami, 2000).

QRD 452 (UDA-245) is a new botanical insecticide and acaricide based on the essential oil of Chenopodium ambrosioides. The active ingredients (composed mainly of terpene, cymene, and limonene with minimal amounts of several other terpenes) are in the essential oil extract of the C. ambrosioides variety near ambrosioides (Chiasson et al., 2004). It was registered on turfgrass in December, 2008, and was approved for ornamental crops on June 30, 2010, by EPA. The terpenoid contained in a product is toxic to insects and is compatible with hymenopteran parasitoids. Phytotoxicity trials suggested that QRD 452 will not injure flowers or leaves of 15 bedding plant species tested at 0.5% necrosis (Chiasson, 2004).

Metarhizium anisopliae strain F52 (Met 52) was approved as a microbial pesticide for non-food use in greenhouses and nurseries in 2003 by EPA. The fungus *Metarhizium anisopliae* strain F52 infects insects which contact it. Once the fungus spores attach to the outer surface of the insect, they germinate and begin to grow, then penetrating the inside of the insect and grow rapidly, thus causing the insect to die. *Metarhizium anisopliae* strain F52 can infect larvae and adults of many insects (EPA, 2003).

Some information about the effectiveness of biopesticides QRD 452 and *Metarhizium anisopliae* strain F52 on crops has been reported in the literature. Chiasson et al. (2004) compared the effectiveness of QRD 452 with commercially available pesticides in a laboratory bioassay. The results showed QRD 452 at 0.5% was significantly more effective in controlling mites than 0.7% neem oil, 1.0% insecticidal soap, and the control treatment. Kabaluk and Ericsson (2007) reported that corn seeds treated with Met 52 (*M. anisopliae* conidia) resulted in significant increases in stand density compared to no *M. anisopliae* treated seeds. It also increased plant (stock and foliage) fresh weight when it was applied together with spinosad or with no additional agrichemical on corn seeds. Ansari et al. (2007) reported that the entomogenous fungus *Metarhizium anisopliae* V275 was more efficacious than chemical insecticides (imidacloprid, fipronil) in killing pupae of WFT (70–90% versus 20–50%) in a range of horticultural growing media. Maniania et al. (2002) studied the potential of Met 52 to WFT on chrysanthemum cuttings and reported that Met 52 could significantly reduced in both the adult and larval populations of WFT.

There is little information about the effectiveness of QRD 452 and Met 52 to control WFT on impatiens. Effects of these pesticides on the two spotted spider mite, European red mite, black vine weevil, and WFT has been studied by some researchers (Chiasson et al., 2004; Bruck and Donahue, 2007; Maniania et al., 2002). Since crop and insect interactions can be very complicated, we want to make a complete cost and benefit comparison among traditional and biopesticides to compare the efficacy and cost during impatiens production, which will contribute to the objectives.

2.1.2 Research on Economic Analysis of Experimental Outcomes

As noted above, various pest management strategies have been tested, but there are few references in the literature that identify strategies resulting in cost reductions or other advantages such as reduction in environmental degradation. In general, there appears to have been little work that documents or measures the impact of WFT on other greenhouse foliage or flowering plants, or on costs of alternative pest management strategies. No work was found that applied directly to alternative pest management strategies for controlling WTF in impatiens.

2.1.3 Cost and Production Theory

The discussion below provides the overall cost framework that is critical to firm analysis, and discusses applications of analysis in a variety of situations. Growers require management tools that can be used to compare production efficiency and costs of their production operations to other firms in similar markets. Cost analysis is a good starting point common to all economic evaluation methods. Cost theory offers an approach to understanding the costs of production for an individual or a firm to determine the level of output that reaps the optimal level of profit at the least cost (Pindyck and Rubinfeld, 2001). When evaluating the production expenses of individual crops, fixed and variable costs must be determined. Fixed costs are those incurred regardless of the level of output. Variable costs are costs that vary with output which include specific costs such as seed, containers, fertilizers and plant material. To be profitable, product prices must include fixed costs and variable costs (Pindyck and Rubinfeld, 2001). Usually the cost function is specified as $C= F(Y, P)$, where C is the total cost, Y and P are vectors of price of output and input, respectively.

Production is an economic behavior which transforms inputs into outputs. Inputs usually include land, labor, and capital, plus raw materials and business services. The efficiency of transformation of inputs into outputs is determined by the technology in use. Limited quantities of inputs will yield only limited quantities of outputs. The relationship between the quantities of inputs and the quantities of outputs produced is called the "production function." It is described by the equation $q = f(k, l)$, where q represents quantities of output, k denotes the amount of capital, and l denotes the amount of labor (Pindyck and Rubinfeld, 2001). In economics, the key point for a firm is how the levels of output and inputs are chosen to reach profit maximization under the existing technology. This can be expressed as a profit equation: Max $\pi = p\ q(g(f, l)- c(r(Y, P))$, where π is profit, p is the market price of output, and q is the quantity of output.

Since there exists the law of diminishing returns, the marginal productivity of the variable input will eventually decline. A decision rule for a firm is to produce at the point where marginal revenue equals marginal cost, which is expressed as $\Delta\pi/\Delta q = \Delta\ \text{revenue}/\Delta q - \Delta\text{cost}/\Delta q$. At this point, a firm could make the decision whether to produce or not in order to reach resource optimal allocation (Pindyck and Rubinfeld, 2001). If $\Delta\pi/\Delta q>0$, the firm might choose to remain in production. If $\Delta\pi/\Delta q<0$, the firm might stop production.

2.2 Budgets

There are four general types of farm/ranch budgets: enterprise, whole-farm, cash flow, and partial. A whole-farm budget is normally used to compare alternative farm organizations under different cropping or production patterns. A cash flow budget is concerned with the timing of receipts and expenses for a production period (Riggs et al., 2005). Thus, these two budgets are not appropriate to the objectives of this study, which is related to greenhouse production with almost the same production process for seasons and usually operated by one owner. Thus, we focused on enterprise budget and partial budgets.

Enterprise budgets are an important tool for planning and for ongoing farm financial management. Budgets are used as a starting point for individual producers to estimate the potential revenue, expense and profit for some specific enterprises and situations (Born, 2004). Producers must consider several economic questions before making a production decision. These questions include: Which crop and variety will be produced? How many acres will be produced? Which production system will be selected? Will the revenue be greater than the expenditure on production? (Smith et al., 2009). Producers will determine their production strategies based on the answers to these questions. This process is actually the basic procedure of budgeting with regard to the coordination of resources, production, and expenditures. Revenue, cost and profit are the three basic components of an enterprise crop budget. Revenue is derived from the product sale. Profit equals revenue minus cost. Cost is all the expenditure of fixed and variable costs including machinery, fertilizer and electricity fees, etc. (Hanson et al., 1991).

The partial budgets method is a practical way to compare changes in production costs and revenue since it requires minimal data compared to other budgets. It has been used largely when production systems are subject to change, to compare two or more alternative sets of production practices (Lu et al., 2003). All systems under comparison must be under the same production conditions, have the same fixed cost and vary only in explicitly specified components (Labarta et al., 2002). The main point is to calculate the net change in return, which subtracts the total cost from the total return. The key requirement for using the partial budgets method is to identify all the changes (positive and negative) produced by shifting from a standard input to a proposed alternative (Labarta et al., 2002).

Budgeting is useful for estimating costs and returns on enterprises currently or in the future. Producers may strive to optimally balance the use of conventional pest control products and biological control products while maintaining the desired quality level of the products to increase profit. Floriculture crops are valued based on their aesthetic value, which is diminished by the visual presence of pests, as well as by the damage caused by them. Therefore, high quality plants with no pests have been a goal of most floriculture producers (Schumacher et al., 2006).

2.2.1 Bioeconomic Model

In prior literature, some economic models have been developed to evaluate the returns of production. But fewer models have incorporated pest control. In order to get an optimal decision rule for pest control as well as profit maximization for an ornamental crop, Schumacher et al. (2006) developed an optimal pest control model based on other authors' model for the ornamental crop ivy geranium as the following formula (Equation 1). This model was structured on a single ornamental crop, one pest, and one predator within one crop cycle. Based on this model, growers could determine the level of conventional pest control, introduced biological control (e.g. natural enemy) and horticultural control (e.g. land sanitation) in each period that maximized the benefits of plant production. Optimal trajectories for chemical and biological control can be derived from the first order conditions of Equation 1. Growers had four options to use a chemical pesticide and/or introduce predators to control for pests: single, simultaneous, cyclical or no control. The specific underlying assumption was that a large population of pests can cause major damage to the crops. The functions and parameters the authors provided in the paper were specified for ivy geranium (*Pelargonium peltatum*). Its major pests are the twospotted spider mite (*Tetranychus urticae)* and a predatory mite (*Phytoseiulus persimilis).*

$$\mathrm{Max}_{u1t,u2t,u3t\geq 0}\{\beta^{T}\ B(Q(\alpha T,gT,pT);Z)+\beta^{T}\ F(\,gT,pT)-\textstyle\sum_{t=0}^{T-1}\beta^{t}\,C(u1t,u2t,u3t;Z)\ \}\ldots(1)$$

Where: *B*(*Q*(*aT*, g*T*, p*T*);Z): concave benefit function,
C(*u1t*, *u2t*, *u3t; Z*): a convex cost function,
Q(aT, g*T*, p*T)*: a continuously differentiable function that represents the total quality from the joint influence of plants and visual presence of insects.
F(gT, pT): expected net benefits based on the state variables at terminal time T.
(See Schumacher et al. (2006) for other details.)

This procedure and equation could possibly be applied to other crops and pests. However, the parameters of those functions related to other pests and crops would be re-estimated because different pests have different growing stages, performances and population dynamics, and different crops have different growing styles. In addition, functions such as Q and F require large amounts of data, consuming time and other resources. The environmental and weather conditions would affect the Q and F functions. It is not clear that the benefit of additional precision in pesticide amount and timing would exceed the cost of determining those parameters for solving problems in the field.

2.2.2 Multiperiod Profit Maximizing Model

Gillespie et al. (2008) reported a multiperiod profit-maximizing conceptual economic model related to cow-calf production (Equation 2). This equation provides the maximum profit of cow-calf production associated with optimal input usage in selecting a grazing strategy. Production functions for cow f(.) and calf g(.) must be available to solve for profit maximizing input levels, and data are rarely available to determine these functions for specific conditions (Gillespie et al., 2008). The authors compared costs and returns among low/ medium / high stocking rates-continuous grazing and rotational grazing at a high stocking rate in the U.S. Gulf Coast region. Since the data provided the comparison of cost and benefits, partial budgeting was used to determine the impact of different stocking rates and grazing strategies on profit by changing stocking rate and/or grazing method. They concluded that rotational grazing had the least net return among the four different strategies.

$$\max \pi(x) = \sum_{t=1}^{\pi} \pi_t \; (x_{it})$$

$$= \sum_{t=1}^{T} (1-\gamma)^t \left\{ \frac{1}{Y} p_{cow,\ t} \; f(x_{it}) + p_{calf,\ t} \; g[f(x_{it})] - \sum_{i=1}^{n} \omega_{it} x_{it} \right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{.... (2)}$$

Where $\pi_t(.)$: profit at year t, T: the number of years, x_{it} : the amount of input i used at time t, Y: the useful life of the cow in years prior to culling, p_{cow},t : the price of the cull cow at year t, p_{calf},t : the price of the calf at year t,
f(.): the production function for the cow, g[.]:the production function for the calf,
ω_{it} : the price of input i at year t.

2.2.3 Net Present Value Model (NPV)

Other models, like net present value, have been used to analyze costs and profitability. For instance, Pandey et al. (2006) developed an NPV model to evaluate the optimum size of rainwater storage used for a rice-fish integrated production system revenue for a 2-3 year period. Net present value of irrigation systems was computed by subtracting the total costs from the present worth value of returns (Equations 3, 4, 5). This model is appropriate for investment

$$NPV = W_{RE} - W_{AC} \quad \text{.. ……………….……………………………..…………} (3)$$

$$W_{RE} = \sum_{t=1}^{n} \frac{R_{E,t}}{(1+i_r)^t} \quad \text{…………….………………….………….…...…..} (4)$$

$$W_{AC} = \sum_{t=1}^{n} \frac{C_{A,t}}{(1+i_r)^t} \quad \text{…………………………………….........……….....} (5)$$

Where RE, t and CA, t are the returns and annual costs at the t^{th} year, respectively.
WRE: present worth value of returns. WAC: annual costs. ir: an interest rate.
n: economic years of life of a reservoir.

evaluation of a firm for this 2-3 year period, and can be generalized to any number of years. The NPV concept converts all future cash flows (positive or negative) into present values. NPV indicates the difference between the present value of cash inflows and the present value of cash outflows. If NPV is positive, it is an investment for the firm to consider, although alternative uses of resources might still be compared (Pindyck and Rubinfeld, 2001). This scope of analysis was limited to the capital investment, plant operating cash flows, and logistics costs, but could have included other costs or revenues. This is not appropriate to our objectives because a multiperiod analysis is not required.

2.2.4 Partial Budgets Model

Wanyama et al. (2004) used partial budgets to analyze insecticide use and the potential for Bt Maize varieties in the control of stalk borer in Kenya. In Kenya, maize yield at first drastically increased up to the 1970s since the introduction of improved maize varieties; but has declined since then. The authors indicated that nutrient mining, sub-optimal input use and insect pest damage (stalk borer was the major pest) were the three main factors which caused the yield to decrease drastically. They evaluated the economic impact of Bt varieties which were tolerant to stalk borer and the types of insecticides used by farmers. Net benefits (NB) were gross benefits (net maize yield [Yi] multiplied by maize price) minus total variable costs (TVC: all inputs [Xi] multiplied by their respective prices [Px]). The equation was $NB = Y_i P_y - X_i Px$. This approach allowed the researchers to compare the cost and profit potential difference between use /non-use pesticides and resistant/nonresistant maize varieties planted in 6 different zones (low tropics, moist transitional tropics, high tropics, moist-mid-altitude zones, dry transitional and dry moist tropics). The authors concluded that if Bt maize were introduced in Kenya it would likely to reduce losses caused by stalk borer by 15%.

Other uses of partial budgets include analysis of whether production alternatives change profitability. Lu et al. (2003) used partial budgets to analyze the effect of management intensity on cost and profit of three watermelon cultivars. Carlson (2007) used partial budgeting to evaluate the costs and benefits in a field rice study by comparing the weed control, yield and revenue with alternative herbicide programs. Mite (2005) used partial budgets to determine economically optimal fallow weed control programs for alternative production situations for sugarcane producers. Gillespie et al. (2008) used partial budgets to investigate the role of labor and profitability in choosing a grazing strategy for beef production in the U.S. Gulf Coast region. Andino (1999) evaluated the cost and benefit of colored plastic mulch on watermelon production by using partial budgets. Wanyama's study and other references illustrated that partial budgets could be a useful tool to analyze the costs and benefits of controlling WFT on impatiens production in the greenhouse production situation.

2.3 Linear Programming Model

The obligation to meet infinite needs with restricted resources is one of the biggest challenges encountered in the market today (Ozsan et al., 2010). Linear programming (LP) is a powerful analytical tool that can be used to determine an optimal solution that satisfies the constraints and requirements of the current situation (Betters, 1988).

This method consists of three quantitative components: (1) objective function (maximization of profit or minimization of costs); (2) constraints (limitation of production sources); and (3) decision variables (Chinneck, 2004). In formulating the linear programming problem, the assumption is that a series of linear (or approximately linear) relationships involving the decision variables exist over the range of alternatives being considered in the problem (Chinneck, 2004).

LP output not only provides an optimal solution, it also provides sensitivity analysis. Sensitivity analysis evaluates how changes in the objective function coefficients affect the optimal solution of a linear programming model. It could examine how well the changes of objective function coefficients and the right hand side value could affect the optimal solution (Anderson et al., 2000).

LP has been used in the evaluation and optimization of raw material resources, capital, machinery, equipment, time and manpower under certain restricting circumstances to get the most benefit (Han et al., 2011). Hassan (2005) used a linear programming model to determine the optimum cropping pattern as a prerequisite to efficient utilization of available resources of land, water, and capital for Pakistan’s agriculture. Bretas (1991) reported a general linear programming model which was developed to determine an income-maximizing set of management activities for a cash-crop farm subject to groundwater quality standards for pesticide contamination. Ozsan et al. (2010) reported that a linear programming model was used to determine the maximum profit in marble processing plants.

There is little information about how to obtain an optimal pesticides application strategy and achieve minimum production cost and high plant quality in a greenhouse. In this study, we present a conceptual linear programming framework by which agriculturalists or growers could examine the cost and efficiency of pesticide application in the management of WFT on impatiens in a greenhouse. Growers and managers may understand that the LP model helps to allocate the resources most efficiently, particularly in situations where important constraints are placed on the actions that may be taken. Sensitivity analysis allows evaluating the impact of pesticide price variability on optimal WFT control programs. A post optimal analysis of the established production minimization model would be attempted to help the growers in adjusting their decisions in facing increases or decreases in demand, resource prices and availability of raw materials.

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Chapter 3. A Partial Budget Analysis for Western Flower Thrips Management on Impatiens Grown in Greenhouses

3.1 Introduction

Impatiens is among the most important bedding plant crops in the United States (Ugine et al., 2007). The wholesale value of impatiens in the U.S. was around $153 million in 2008 (USDA, NASS, 2008). Impatiens grown in greenhouse conditions is prone to attack by western flower thrips (*Frankliniella occidenttalis,* Pergande). WFT is a serious pest of over 200 species of vegetables and ornamental crops worldwide (Arthurs and Heinz, 2006). Damage to impatiens occurs in two distinct ways: (1) the direct feeding damage which causes surface blemishes, leaf scar, flower deformation, and growth distortion, and (2) the indirect damage from disease, particularly impatiens necrotic spot virus and tomato spotted wilt virus, which is facilitated by direct feeding damage (Cloyd, 2009).

The regular use of chemical insecticides in order to control thrips in greenhouses raises many concerns due to direct and cross resistance to commonly used insecticides (Arthurs and Heinz, 2006). Biological chemicals which come from natural plants, or microbes, degrade quickly after application. Little or no toxic residues would be left in the environment, thus largely avoiding the pollution problems caused by conventional pesticides (Kogel et al., 2004b). Due to the advantages of biological chemicals, people have more and more interest in biopesticides. The overall goal of this project was to improve the efficiency of WFT management in greenhouse impatiens production in Louisiana. The cost effectiveness of newly developed biological chemicals (Met 52, QRD 452, and combinations) in preventing thrips was evaluated in this study. Since a key resistance-management practice to avoid pesticides resistance is to use chemical rotation programs, some typical strategies (different chemical rotations) and their costs were also discussed in this study. The issues presented should provide insight on the effectiveness of new biological chemicals dealing with WFT and the costs of different insecticide schemes.

Repeated use of the same class of pesticides to control pests can cause undesirable changes in the gene pool of a pest. When a pesticide is first used, a small proportion of the pest population may survive due to its distinct genetic makeup. These individuals pass along the genes for resistance to the next generation. The proportion of these tolerant individuals in the population increases, while the more susceptible share of the population diminishes. Through this process, the population develops resistance to the pesticide. To counter this effect, the rotation of insecticides with different modes of action is a recommend approach (Cloyd, 2010). Biopesticides are alternatives that may be used in such rotation.

Pesticide product labels provide critical information about how to safely and efficiently use pesticide products, and are the source of application rates. Specified amounts of each chemical are added to water to get the required rate solution in a tank.

Two or more pesticides may be applied simultaneously to make application convenient and save time. They can be mixed in one tank if their labels indicate compatibility. Reasons to avoid mixing are that they may react with each other and produce new compounds that have no impact on target pests; the reaction may form precipitates that interfere with the operation of the sprayer; or that pesticides may separate, which could cause differences in application as the concentrations in the tank vary.

3.1.1 Flow Chart Description of Situations Chosen for Partial Budgeting

The criteria for choosing strategies for which partial budgets were prepared are presented in general form in Figure 1. A variety believed to be thrips-susceptible, Dazzler Violet, was identified. Results from experiments that evaluated the impact of alternative rates of N and P on plant growth and quality suggested whether a different budget was needed. Low and high rates were illustrated in the chart, but multiple rates were evaluated. If there was no difference based on outcomes of experiments, one budget sufficiently represents the situation. Following that choice, a series of pesticide strategies were developed based on the experiments, based on control strategies used by growers, and based on control strategies recommended by research scientists. These strategies included both conventional, commonly used products and the biopesticides.

Only one branch of the chart was illustrated in Figure 1. The other branches would be analogous, and a separate chart could be used to represent the thrips-resistant variety Super Elfin Red.

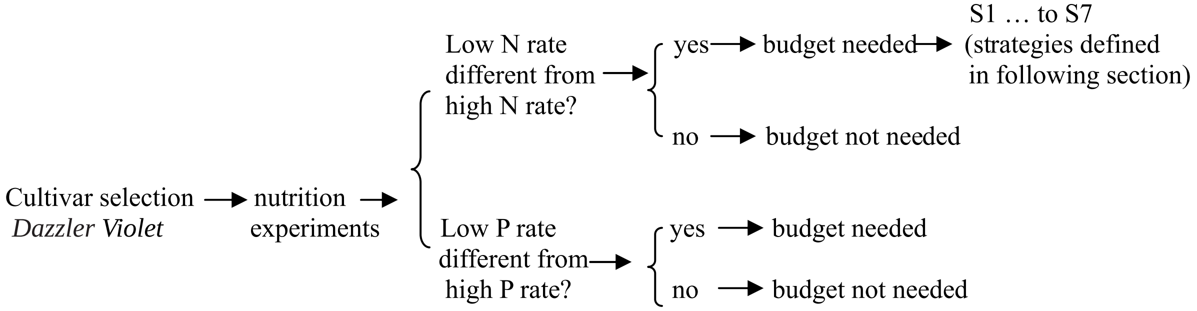

Figure 1. Flow chart of cultivars, fertilizers and pesticides schemes

3.1.2 Background on Biological Pesticides Met 52 and QRD 452

QRD 452. This is an essential oil extract of *Chenopodium ambrosioides* nr. *Ambrosiodes*, so it is a bioinsecticide. As a naturally occurring compound, it is not expected to be environmentally hazardous (EPA, 2011); however, the product was not labeled for use in greenhouse production of ornamentals at the time this project began. Recommendations for the use of a pesticide on a crop cannot be made until studies of its persistence have been carried out

(Sharma et al., 2007). It was labeled and available for outdoor use under the trade name Requiem. The developer AgraQuest had indicated work toward a label for the product for greenhouse ornamentals. It had been noted to have action on one or more stages of the thrips' life cycle. Its mode of action is that softening of the cuticles of insects leads to disruption of respiration (EPA, 2008). Chiasson et al. (2004a) reported that 0.5 % QRD 452 was effective against adult twospotted spider mite and the European red mite in a laboratory bioassay. Chiasson et al., (2004b) evaluated QRD 452 in controlling WFT in a laboratory bioassay. Results indicated it was significantly more effective than neem oil, insecticidal soap or the control treatment. Thus, it would represent an alternative product with environmental advantage to address the resistance issue. Overall, however, little research-based information about QRD 452's impact on thrips was available in the literature. For that reason, a request was made to AgraQuest's research scientists (personal communication) to provide information about efficacy. These representatives responded that QRD 452 would not be made commercially available for greenhouse production of ornamental plants at this time. However, the product remains available to researchers for testing, was labeled for other applications, and was available in the market, so it was retained as one of the biopesticide alternatives in potential control rotations.

Met 52 (*Metarhizium anisopliae* Strain F52). This is a recently developed microbial insecticide, a deuteromycetous fungus with a host range primarily affecting coleopterans of the families Elateridae and Curculionidae (EPA, 2000). Based on information from Novozymes (personal communication), Met 52 is available for greenhouse application in European countries and Canada. It is labeled in the U.S. for outdoor application on lawns for control of pests, such as ticks, under the trade name TICK-EX. Met 52 is sold in granular form for incorporation into media to act against eggs, instar and pupae stages of thrips, and in emulsifiable concentrate (EC) form for foliar application as a spray. The company indicated that Met 52 would be commercially available in the western U.S. late in 2011, with national distribution to follow.

Met 52 is effective because *Metarhizium anisopliae* fungus spores can infect different developing stages of insects. Spores germinate on the surface of the insect, then penetrate into the insect, causing the insect to die (EPA, 2000). Effectiveness of Met 52 was reported in the literature review in Chapter 2. Since the product's effect is through production of spores, it is effective only after a period of reproduction.

3.1.3 Sources of Data Used in the Study

As discussed in the introduction chapter, a USDA/PMAP grant funded a series of experiments that were intended to answer questions about resistant and susceptible cultivars' response to thrips pressure, about the role plant nutrition plays in being more or less attractive to thrips, and the role of biopesticides as part of resistance strategies. In addition to the experiments described in Chapter 1, information used to choose parameters came from informal interviews and discussions with growers and representatives of the companies that brought the biopesticides to the market.

3.1.4. Discussion of Informal Data Collection

To get more detailed information about biopesticides and different pesticide schemes used to control thrips on impatiens production, greenhouse growers located in Louisiana were interviewed about impatiens production procedures. Data included typical greenhouse size and bench/tray arrangement, tray capacity in a greenhouse, methods of estimating thrips population (yellow sticky cards, for example), pesticide preparation, spray and cleanup times and typical length of a crop cycle. It was common to have a regular, planned schedule of pesticide applications. Two of these interviews were in person, while four others were by telephone.

3.1.4.1 Information from Companies Marketing QRD 452 and Met 52.

There was scant literature on efficacy of these two biopesticides; however, both had been tested at some length as part of the product registration process. Requests for publicly available research were made to company representatives - Novozymes for Met 52 and AgraQuest for QRD 452. Information that was provided included:

— QRD 452 had been considered for registration on greenhouse ornamentals, but the company declined to take that action and did not disclose the reason for that decision. The product is registered for selected outdoor applications under the trade name Requiem. Product price was available because of this registration, and product for testing was available to research scientists.

— Met 52 in granular form and emulsifiable concentrate form have been used in Europe for a period of years. Its label in the United States for application on ornamental plants in greenhouses is recent, and the product was scheduled for commercial sale on the west coast of the U.S. late in 2011. The company representative indicated that Met 52 should provide acceptable control of thrips if applied regularly.

3.1.5 Pesticide Programs Used by Louisiana Growers.

Some of the pesticide schemes were based on production practices of growers. Initially, it was expected that additional information about the use of biopesticides and their effectiveness would be gained; however, it appeared that biopesticides were seldom used in Louisiana. Reasons given included that (i) thrips is not a problem, (ii) conventional products are effective, and (iii) there is a risk associated with new products (they knew how to use conventional products, but were unfamiliar with biopesticides).

University horticulturalists assumed a production cycle of 8 weeks. Some growers, however, had shorter cycles of about 6 weeks. Generally, growers followed one of two approaches. First was a pre-determined schedule of application of products, typically at 7 day intervals. Second was close observation of the crop to spot problems (scouting), followed by application as needed. Two typical pesticide schemes from growers (strategies 1 and 2) shown in Table 3.2 were used to compare their efficiency and cost with those of biopesticides.

3.2 Method - Partial Budget Construction

Partial budgeting is a planning and decision-making framework used to compare the costs and benefits of alternatives faced by a farm business (Roth and Hyde, 2002). In a partial budget, only activities that will be changed are evaluated for their ability to increase or decrease income in the farm business. In this study, all aspects of farm profits that are unchanged will be ignored.

3.2.1 Costs for Partial Budgets

Fixed costs include, but are not limited to, greenhouse, facilities, equipment depreciation and interest. The variable costs include: cultivar, fertilizer, chemical inputs, fuel, labor (i.e., harvest, transport), operating costs of machinery, and other inputs (i.e. utilities). Fixed costs do not change with levels of output. Variable costs, such as utilities, containers and other inputs, do change across production cycles. Variable costs were computed and analyzed on a per unit basis. Variable costs such as fertilizers, pesticides and labor were of interest in this study. Marketing, transportation and other inputs were assumed to be equal across treatments. As a result, changes in production costs were due to different fertilizer usage, labor cost and variations in pesticides programs.

In this study, only total production cost was estimated in the partial budgets. The estimation of revenue was not included for the following reasons: (1) some plant quality evaluations were taken as part of the scope of this project, but not for all the strategies; (2) there was little information in the literature review that related plant quality to pesticide control strategy, and it appeared that plant quality was assumed to be related to thrips mortality; (3) there appear to be two classes of impatiens sold – plants that meet expected quality at the market, and others that must be sold at discount due to lower quality. Any other plants are discarded. Growers did not have estimates of the shares of plants in these classes in general, and particularly by strategy. For these reasons, differences in revenue were difficult to estimate and were not included in these partial budgets.

3.2.1.1 Fuel Cost

Several kinds of sprayers may be used for pesticides application. Dramm Hydra sprayers are one example. It is a popular commercial greenhouse sprayer in today's market (Plant Produce and Service, INC, 2009). Each Dramm Hydra sprayer is powered by either a 1.5 horsepower electric TEFC (Totally Enclosed, Fan Cooled) motor or a 5.5 horsepower Honda gasoline motor. The reference indicates that the gasoline motor consumes 200 grams gasoline per hour per horsepower (http://wenwen.soso.com/z/q233977950.htm). In this case, the 5.5 horsepower gasoline motor consumes 1100 grams of gasoline per hour. The fuel cost was calculated by multiplying the fuel consumption rate per hour times the price of gasoline. Thus, fuel cost per greenhouse equals gasoline price times gallons per hour times operation time (Cáceres, 2005).

3.2.1.2 Labor Costs

Labor cost was determined as the hourly labor rate multiplied by labor performance time. Labor included machine setup, machine operation, pesticide spray, machine service and personal scouting in greenhouse. The minimum wage rate was $7.25 per hour regulated by federal government (http://www.dol.gov/whd/minwage/america.htm#Louisiana); however, a full time labor cost was not only based on an hourly minimum basis, but also benefits such as medical insurance and social security. Based on these considerations, a hired farm laborer was paid $9.60 per hour (Salassi and Deliberto, 2012). Manager labor was charged at $15.60 per hour, which included a basic wage rate of $12.00 per hour plus additional costs (27.65%) for social security, Medicare, and workman's compensation (6.2%, 1.45% and 20.0% respectively). The higher wage rate was charged for scouting because an expert with higher skills might be needed for scouting (Salassi and Deliberto, 2012).

Traditionally, growers use sprayers to apply insecticides. Based on the informal survey of growers, the setup and cleanup time for each application was around 25 minutes. One pesticide application time was estimated at 25 minutes for a greenhouse based on experience and reports from growers. These costs were a component of the partial budget.

3.2.1.3 Chemical Costs

Market prices were used to estimate the costs of insecticides and fertilizers in this study. Input prices were from companies or suppliers of agricultural chemicals and services online. For example BWI Company, Inc. (http://www.bwicompanies.com), B&T Grower Supply, Inc (http://btgrowersupply.stores.yahoo.net/insecticides.html) and Waldo Grower Supply Catalog (2008) were the major sources of prices.

Chemical application time and rates were estimated based on the informal survey. Growers usually purchase plugs from the market and transplant them into 4- inch pots in a greenhouse. Market size is reached in about 8 weeks. Thus 8 weeks was chosen as the production cycle.

3.2.1.4 Fertilizer Costs

The informal interviews indicated that growers purchased a complete analysis fertilizer, typically 17-5-24 ($N-P_2O_5-K_2O$). The common greenhouse size is 30 ft. x 96 ft. which can hold about 1000 flats of size 20.5 inches x 10.5 inches, and the production cycle is eight weeks from plug to mature crop. An application rate of 210 ppm is a weekly fertilizer use rate of 6.98 pounds, while the application rate of 105 ppm was a weekly rate of 3.49 pounds. These rates were used in the partial budgets.

3.2.2 Considerations in Choice of Pesticide Schemes

Rotation schemes are one of the first lines of defense against pesticide resistance. Control products have different modes of action that can delay thrips resistance development and provide a sustainable and effective approach to control thrips (Cloyd, 2010). A mode of action (MoA) classification scheme was developed and endorsed by IRAC (Insecticide Resistance Action Committee), an international group of more than 150 members of the Crop Protection Industry. Its goal is to work as a technical group of the industry association CropLife to communicate, educate, prevent or delay the development of resistance in insects and mite pests in industry (http://www.irac-online.org/about/irac/). Resistance arises through the over-use of an insecticide against a pest species. This method of selection of resistant pests causes the evolution of populations that are tolerant to that insecticide. Resistance is commonly developed based on a genetic modification of a target site. The IRAC MoA classification provides guidance to the selection of insecticides or acaricides (any drug or formulation for killing mites or ticks) to growers, advisors, consultants and professionals to encourage effective and sustainable use of insecticides and acaricides.

3.2.3 Limits Imposed by the Pesticide Label

The major chemicals used in this study were Met 52 and QRD 452. In the informal survey of growers, the products used were collected and added to the list. The company representatives were asked to identify thrips control products they had observed in use in greenhouse production situations of impatiens. Subsequently, product formulations and label application recommendation limits for all these products were collected and shown in Table 3.1. Important concerns about application of major pesticides studied in the study on their labels were briefly discussed.

The old label of Conserve SE regulated that the maximum application times was 10 times a year before 2006 (label code: D02-090-010). Researchers have demonstrated that overuse of Conserve led to thrips resistance (Bielza et al., 2007). Therefore, Conserve's label has changed in recent years. The number of permitted applications has been reduced to 5 or 6 times (D02-090-013) per year. The production period of impatiens in a greenhouse is around 8 weeks. Thus there may be two or more impatiens production cycles in spring and fall. The recommendation of a single application of Conserve per production cycle was adopted.

Met 52 has two forms: Met 52 Granular and Emulsifiable Concentrate (EC). Granular is incorporated into growing media or soil at a rate of 0.5 kg/m^3 in order to protect crops. It must be incorporated thoroughly and evenly mixed into the media. Met 52 Granular can be used at all crop growth stages (http://www.fargro.co.uk/prodmanl/met52-0111.pdf). Met 52 EC may be used for foliar applications to control insects with a high reproductive potential. There is no application limit for this product. However, it is better to begin applying Met 52 EC at early stages since it takes time to be effective. Applications may be repeated at 5 to10 day intervals to match need based on insect population and plant quality goals.

According to the label, QRD 452 (REQUIEM EC) is a contact insecticide and thorough coverage is necessary for optimum thrips control. QRD 452 also needs to be applied at early stage of the pest cycle before thresholds are reached. The maximum application times of QRD 452 was less than 10 times per crop production cycle. Other products also contain label recommendations with respect to number and times of applications (Table 3.1).

Table 3.1 Label statement of limits on pesticides application rate ranges and number of applications for greenhouse ornamental plants

Name	Type	Rate range per 100 gal of water	Limit
Avid	insecticide	4 to 8 oz.	No limits stated
BotaniGard 22 WP	biological insecticide	16 to 32 oz	No limits
CapSil	surfactant	6 to16 oz	No limits
Conserve SE	pesticide	8 to 20 oz	No more than 6 times in a year, never apply more than 3 consecutive applications
Met 52 EC	biological insecticide	16 to 32 oz	No limits
Merit 75 WP	insecticide	0.5 to 2 oz	No limits stated
Ornazin 3% EC	botanical insecticide	8 to10 oz	No limits stated
Orthene 75% SP	systemic insecticide	0-8 oz	No more than 2 time per year
Pedestal	insecticide	6 to 8 oz	No more than 2 times per crop per year
QRD 452 EC	biological insecticide	64 to128 oz	No more than 10 times per crop production cycle
Talstar EC	insecticide	10.8 to 21.7 oz	No more than 10 times per year
Tristar 30 SG	insecticide	4 to 8 oz	No more than 5 times per year

Note: SP: soluble powder, WP: wettable powder, SC: suspension concentrate, EC: emulsifiable concentrate, SG: soluble granular

3.2.4 Typical Industry Approaches to Thrips Control

A seven-day interval between applications was chosen for all pesticide schemes. This weekly schedule is common among growers because it generally provides sufficient protection and is easy to recall. A five-day interval between applications is recommended for susceptible cultivars or heavy thrips pressure. The seven-day interval was chosen for the partial budgeting procedure.

Pesticides used in alternative partial budgets were (i) typical combinations identified by growers; (ii) combinations chosen by experts to prevent or minimize development of resistance to thrips by rotating insecticides with differing modes of action (Cloyd, 2010); (iii) use of the individual biopesticides QRD 452 and Met 52, and combinations of the two, and (iv) combination of conventional chemicals and scouting. Because the best way to prevent or minimize resistance development of thrips was to rotate insecticides with variable MOA (Cloyd, 2010), the pesticides in the 6 strategies have different modes of action according on the IRAC modes of classification.

To make a broad range of partial budgets, some typical schemes were chosen to represent different kinds of growers located in Louisiana. The insecticides used in strategy 1 were commonly used and effective products available in the current market. The conventional pesticides Merit, Decathlon, Avid, Orthene and Tristar were included in strategy 1. They have been used extensively in commercial outdoor plant nurseries as well as in greenhouse production, and for lawn and landscape insect control. They are effective, broad spectrum, water soluble insecticides used against many kinds of aphids, insects and pests. Ornazin (a biopesticide) is a natural insect growth regulator extracted from the seeds of the tropical Neem tree (Azadirachta indica) (http://www.sepro.com /default.php?page=ornazin), and was included in this grower strategy.

Another control scheme focused on scouting the thrips situation regularly (Table 3.2, strategy 2). In this scheme, no pesticides were applied at weeks one to four. Avid was applied at week five. Talstar and Conserve were applied at week six. From week one to four, scouting was conducted to examine the thrips situation. The number of thrips on the crop is estimated by visual inspection, or counting the thrips captured on blue or yellow sticky cards placed appropriately in the greenhouse. Additionally, scouting could detect seasonal trends of thrips populations throughout the year and assess the effectiveness of management strategies implemented (Cloyd, 2010). Scouting hours in the scheme were assumed to be 10 minutes per day. In this scheme, it was suggested that the typical first pesticide application would not occur until four weeks after transplanting. Pesticides then were only applied at the fifth week and the sixth week. In this case, the crop was marketed after six weeks.

The biopesticide schemes of this study were designed to compare estimated cost of controlling thrips by using Met 52 and QRD 452 to more traditional controls with conventional pesticides. There was little information about these products in controlling thrips on impatiens since they were newly developed biological insecticides (Ansari et al., 2007; Chiasson et al., 2004). Commercial growers reported no experience with biologicals except for limited familiarity with predators such as specific wasps. Thus, there is a practical need for researchers to provide more biopesticide information to growers. Strategies 3 and 4 were single biopesticide schemes. As shown in Table 3.2, strategy 3 was prepared to estimate the cost of QRD 452 on controlling WFT. Likewise, strategy 4 was conducted to estimate the cost of Met 52 on controlling WFT.

Strategy 5 was designed to alternate applications of Met 52 and QRD 452, with Conserve applied during the seventh week (Table 3.2). The reason for choosing this rotation scheme was that in practice, sequences of chemicals from groups with different modes of action can delay thrips resistance development and provide sustainable and effective approaches to control thrips

Table 3.2 Rotation schemes using products specified and midpoint of label recommended application rate and interval

Name	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Application rate*	Interval In days
Strategy 1	No	Merit Decathlon CapSil	Ornazin Decathlon CapSil	Avid Orthene CapSil	TriStar CapSil	Merit Decathlon CapSil	Ornazin Decathlon CapSil	**	7
Strategy 2	No	No	No	No	Avid	Talstar Conserve	—	midpoint	7
Strategy 3	QRD 452	QRD 452	QRD 452	QRD 452	QRD 452	QRD 452	QRD 452	midpoint	7
Strategy 4	Met 52	Met 52	Met 52	Met 52	Met 52	Met 52	Met 52	midpoint	7
Strategy 5	Met 52	QRD 452	Met 52	QRD 452	Met 52	QRD 452	Conserve	midpoint	7
Strategy 6	BotaniGard	BotaniGard	Pedestal	Pedestal	Orthene	Orthene	Conserve	midpoint	7

* midpoint of label recommended application rate.
** rates used by commercial growers.

(Cloyd, 2010). Conserve was included because it is a particularly effective product which has been in use for about 25 years (Nayak et al., 2005). It has been effective for both ornamental and vegetable crops, and in greenhouse and outdoor production. Conserve was used at the seventh week of strategy 5 because growers often use Conserve to be assured that WFT populations are controlled at the end of the production period and while being sold by the retailer.

Strategy 6 was from the publication of Kansas State Research and Extension with minor modification. In this article, Cloyd (2010) provided 5 rotation programs which involved commercially available insecticides with different MOA. The chosen scheme (strategy 6) consisted of BotaniGard, Pedestal, Orthene and Conserve. BotaniGard (a biopesticide) has been used for the control of pest such as thrips and grasshoppers by growers for more than 10 years (Mommaerts, 2009). BotaniGard contains spores of the fungus *Beauveria bassiana,* strain GHA. The spores adhere to the host and germinate, penetrating and eventually killing the pest (http://www.growninmyownbackyard.com /BotaniGard.html). In strategy 6, each pesticide was applied in two consecutive weeks. Because of the issues related to resistance with Conserve, scientists recommended application of Conserve only once per crop cycle. This scheme has products with different MOA that the growers can use in a rotation program to alleviate problems with WFT and also minimize the prospects of resistance.

3.3 Results and Discussion

The economic analysis for the different strategies was conducted by using a partial budget procedure. For each strategy, pesticide costs for per application unit were calculated. The pesticides application rates of strategy 1 were obtained from the growers. All other input rates (strategies 2 to 6) used the midpoint of recommended application rates from the label of the specific pesticide. The cost was the key component of the analysis. Labor of pesticides application and labor of fertilizer application were included in each week. The total cost was the sum of all production weeks.

The production costs of adopting pesticides management for WFT control in the six greenhouse strategies were calculated in Tables 3.3 to 3.8. The components of these partial budgets include fertilizer cost, labor costs, pesticides cost and fuel cost. The production costs of the 6 strategies were also presented.

Fertilizer cost: All growers used fertilizer to improve the plant quality during production (Tables 3.3 to 3.8). Thus, fertilizer with analysis of 17-5-24 was applied each week for each strategy. The average cost of fertilizer for each week was $5.24. The total fertilizer cost for 7 weeks was $36.68. Since the production cycle for strategy 2 is 6 weeks rather than the typical 8 weeks, the total fertilizer cost was $31.44. Fertilizer accounted for 19.3% of the total cost in strategy 2. The fertilizer was about 23.9%, 21.0%, 20.9%, 20.3% and 18.6% for strategies 1, 3, 4, 5 and 6 respectively. Among the fertilizer shares of the total cost of all strategies, fertilizer cost of strategy 6 was the lowest share and strategy 1 was the highest share. However, there was only 5.3% difference between the highest and lowest fertilizer share.

Labor cost: The labor cost included preparation before application and clean up after application, the fertilizer application process, and the pesticides application cost. In order to have a detailed conception of all these costs, scouting cost was not included in labor cost (Table 3.9). The average labor cost for each week was $11.04. Thus, the total labor cost for 7 weeks was $77.28 for strategies 3, 4, 5 and 6. Strategy 1 had a $73.88 labor cost since there were no pesticide applications in the first week. Strategy 2 had the lowest labor cost of $31.68 as there were no pesticide applications during the first 4 weeks.

Table 3.3 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using typical prescheduled grower application strategy (1)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week ($)*	Total cost($)
1	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
					subtotal	7.64
2	Merit	tbsp	0.65	4.00	0.65	
	Decathlon	tbsp	3.87	3.80	3.68	
	CapSil	oz	0.82	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.18
3	Ornazin	tbsp	0.54	16.00	2.16	
	Decathlon	tbsp	3.87	3.80	3.68	
	CapSil	oz	0.82	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	25.69
4	Avid	tbsp	2.32	8.00	4.64	
	Orthene	tbsp	0.64	3.60	0.58	
	CapSil	oz	0.82	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	25.07
5	TriStar	oz	0.96	4.00	0.96	
	CapSil	oz	0.82	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	20.82

Table 3.3 continued

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)	Total cost($)
6	Merit	tbsp	0.65	4.00	0.65	
	Decathlon	tbsp	3.87	3.80	3.68	
	CapSil	oz	6.59	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.18
7	Ornazin	tbsp	0.54	16.00	2.17	
	Decathlon	tbsp	3.87	3.80	3.68	
	CapSil	tbsp	0.82	16.00	3.28	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	25.70
					total	153.28

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for Merit is 0.65, input rate 4.00. Thus 0.65 *4.00/4 = 0.65.

Table 3.4 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using scouting with application as needed strategy (2)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)*	Total cost($)
1	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	scouting	hour	15.60	1.17	18.25	
					subtotal	25.89
2	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	scouting	hour	15.60	1.17	18.25	
					Subtotal	25.89
3	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	scouting	hour	15.60	1.17	18.25	
					subtotal	25.89
4	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	scouting	hour	15.60	1.17	18.25	
					Subtotal	25.89
5	Avid	oz	4.65	6.00	6.98	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	23.55
6	Talstar	oz	0.57	16.00	2.28	
	Conserve	oz	4.86	14.00	17.01	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	35.87
					total	162.96

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for Avid is 4.65, input rate is 6.00. Thus 4.65 *6.00/4 = 6.98.

Table 3.5 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using weekly QRD 452 application strategy (3)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)*	Total Cost($)
1	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					Subtotal	24.98
2	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
3	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					Subtotal	24.98
4	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
5	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					Subtotal	24.98

Table 3.5 continued

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)	Total Cost($)
6	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
7	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
					total	174.83

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for QRD 452 is 0.35, input rate is 96.00. Thus 0.35 *96.00/4 = 8.40.

Table 3.6 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using weekly Met 52 application strategy (4)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)*	Total cost($)
1	Met 52 G media treatment	g/cubic ft	0.04	38.00	19.62	
	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	41.82
2	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
3	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
4	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
5	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20

Table 3.6 continued

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)	Total cost($)
6	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
7	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
					total	175.02

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for Met 52 is 30.00, input rates is 0.75. Thus 30.00 *0.75/4 = 5.63.

Table 3.7 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using weekly QRD 452 and Met 52 rotated application strategy (5)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)*	Total cost($)
1	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal / hour	3.00	0.10	0.30	
					subtotal	22.20
2	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
3	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20
4	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
5	Met 52	qt	30.00	0.75	5.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	22.20

Table 3.7 continued

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)	Total cost($)
6	QRD 452	oz	0.35	96.00	8.40	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	24.98
7	Conserve	oz	4.86	14.00	17.01	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	33.58
					total	175.12

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for Met 52 is 30.00, input rates is 0.75. Thus 30.00 *0.75/4 = 5.63.

Table 3.8 Partial budget of estimated production cost per greenhouse for thrips control in impatiens using rotated IRAC mode of action application strategy (6)

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)*	Total cost($)
1	BotaniGard 22 WP	lb	80.00	1.50	30.00	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	46.58
2	BotaniGard 22 WP	lb	80.00	1.50	30.00	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	46.58
3	Pedestal	oz	0.93	7.00	1.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	18.20
4	Pedestal	oz	0.93	7.00	1.63	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	18.20
5	Orthene	tbsp	0.64	3.60	0.58	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	17.15

Table 3.8 continued

Week	Inputs	Application unit	Price per unit($)	Input rates	Cost per week($)	Total cost($)
6	Orthene	tbsp	0.64	3.60	0.58	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	17.15
7	Conserve)	oz	4.86	14.00	17.01	
	fertilizer 17-5-24	lb	1.50	3.49	5.24	
	labor (fertilizer)	hour	9.60	0.25	2.40	
	labor (prep. and cleanup)	hour	9.60	0.42	4.03	
	labor (pesticides application)	hour	9.60	0.48	4.61	
	fuel for sprayer	gal/hour	3.00	0.10	0.30	
					subtotal	33.59
					total	197.44

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the cost per application per greenhouse is the 100 gallon mix divided by 4. As an example, price per unit for BotaniGard is 80.00, input rates is 1.50. Thus 80.00 *1.50/4 =30.00.

Scouting cost: Scouting (or monitoring) is a way to check the situation of thrips present in the greenhouse. Additionally, scouting also helps detect seasonal trends in populations throughout the production cycle. Therefore, growers could assess the effectiveness of thrips management strategies (Cloyd, 2010). Although scouting cost is expensive, visual inspection such as looking into flowers and leaves are additional benefits that may be used to determine the crop quality. Also, scouting reduces pesticide amount use during production.

Strategy 2 had a scouting cost (there is no scouting cost in other strategies). The average scouting cost for one week was $18.25. Thus, the total scouting cost for 4 weeks was $73. The scouting cost accounted for 44.8% (73/162.96) of the total cost of strategy 2.

Fuel cost: Fuel cost came from pesticide applications by using a sprayer. The average fuel cost for each week was about \$0.30. Thus, the total fuel cost was \$2.10 for strategies 3, 4, 5 and 6 since they applied pesticides each week. For strategy 1, the pesticides were applied 6 times; thus, the fuel cost was \$1.80. For strategy 2, the fuel cost was \$0.60 since there was no pesticide application during the first 4 weeks.

Chemical costs: Total pesticide cost for strategy 1 was \$46.19. Pesticide cost was \$26.27 for strategy 2. Strategies 3 (for QRD 452) 4 and 5 (Met 52) had very close pesticide costs of \$58.80 \$59.03 and \$59.10, respectively. The reason was that there was a \$19.62 cost of Met 52 granular treatment (no Met 52 granular treatment for other strategy) in strategy 4 and a \$17.01 cost of Conserve in strategy 5. Thus, although Met 52 was cheaper than QRD 452, the sums of pesticide costs of strategies 3, 4 and 5 were very close. The pesticide cost for strategy 5 (rotation program for QRD 452 and Met 52) was \$59.10. The total pesticide cost for strategy 6 was \$81.43. Thus, strategy 6 has the highest pesticide cost among the 6 programs as BotaniGard was more expensive than any other. Strategy 2 had the lowest pesticide cost among these strategies because the growers only applied pesticides in weeks 5 and 6.

Table 3.9 The fertilizer, labor, scouting, pesticides, fuel and total cost of WFT control strategies for greenhouse impatiens production

	Cost (\$)						
Strategy	Fertilizer	Labor	Scouting	Pesticide	Fuel	Total cost	Cost difference
1	36.68	73.88	0	46.19	1.80	153.28	base
2	31.44	31.68	73	26.27	0.60	162.96	+9.68
3	36.68	77.28	0	58.80	2.10	174.83	+21.55
4	36.68	77.28	0	59.03	2.10	175.02	+21.74
5	36.68	77.28	0	59.10	2.10	175.12	+21.84
6	36.68	77.28	0	81.43	2.10	197.44	+44.16

Total cost: As shown in Table 3.9, the highest total cost ($197.44) was from strategy 6 since BotaniGard had a high market price; followed by strategy 5 which had a total cost of $180.75. Strategy 1 had lowest total cost. The difference between strategies 1 and 6 was $44.16. Strategies 3 and 4 were similar in total production cost.

Except for strategies 1 and 2, the other 4 strategies had the same costs for fertilizer, labor and fuel. They had differences only in pesticide cost. The higher pesticides cost increased the total cost. The sums of fertilizer, labor and fuel costs of strategies 3, 4, 5 and 6 were $116.06. The sums of fertilizer, labor, fuel and scouting cost of strategies 1 and 2 were $112.36 and $136.72 respectively. Compared with that of strategies 3, 4, 5 and 6, the total cost of strategy 1 was the lowest due to its lowest pesticide cost. Strategy 2 had the second lowest total cost resulting from its lowest pesticide cost. Therefore, in this research, the costs associated with thrips control programs were mainly dependent on pesticide cost.

In summary, implementation of different pesticide schemes to greenhouse impatiens would have different total production costs. Strategy 6 had the highest production cost and strategy 1 had the lowest cost. Strategy 1 was less expensive by $44.16 per production cycle for impatiens production in the greenhouse compared with the strategy 6. Strategy 2 had the second lowest production cost among the 6 strategies due to the least pesticides application. The scouting cost ($73) accounted for 44.8% of the total production cost of strategy 2. However, scouting offset part of the pesticides, labor and fuel cost. Strategy 6 had the highest pesticide costs ($81.43), followed by strategies 3, 4 and 5 which were $58.80, $59.03 and $59.10, respectively. The high market price of BotaniGard contributed to the high pesticide cost of strategy 6. In general, the biopesticides had higher prices than nonbiopesticides, thus the treatments applied with biopesticides had increased pesticide costs compared with treatments that included only nonbiopesticides.

Using partial budgeting can easily determine the cost change and compare the difference among them. The growers are most likely to use the schemes which have minimum production cost and high thrips control efficacy. Among the six schemes, strategies 3, 4 and 5 are the schemes to test the efficacy of biopesticides of QRD 452 and Met 52. Strategies 1, 2 and 6 are schemes that have pesticides that are commercially available in the market. These strategies can reduce or control WFT populations to levels that will allow greenhouse producers to grow and sell a high- level quality crop with minimal aesthetic injury.

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Chapter 4. A Linear Programming Model of Optimal Pesticide Programs of Thrips Control on Impatiens in Greenhouse Production

4.1 Introduction

Pest control programs for impatiens grown in the greenhouse have been associated with various factors, such as the prices of pesticides, growers' financial/economic condition, marketing, environmental conditions and weather conditions. Pesticide applications are the key to the effective control of WFT. When growers consider WFT control programs on impatiens, pesticide costs and the benefits of their application are the most critical points. The common production period of greenhouse impatiens is 8 weeks. Pesticide applications are usually applied during the first to the seventh week. Growers usually do not apply pesticides in the eighth week because residual activity continues.

Controlling thrips populations can be challenging. As mentioned in previous chapters, WFT is the most prevalent species for ornamental horticulture crops (Palmer and Vea, 2011). Many old insecticide products are not performing as well as in the past and many new products have been developed. Growers have different considerations in developing their WFT control programs on impatiens. An optimized WFT control program is a preferred choice in business since it can return the same or bigger revenue with less cost.

LP output provides useful information that includes the optimal solution, and sensitivity analysis that evaluates how changes in the coefficients affect the optimal solution of a linear programming model. Using this method, how will the changes of the coefficients and the right hand side value (when considering constraints of the form such as $f(x) \leq b$ or $h(x) \geq c$, the vector (b, c) is called the right hand side value) of a linear program affect the optimal solution (Anderson et al., 2000)? Almost everything is changing in the real world, such as raw material prices, pesticide prices, or market demand increases or decreases. The mathematical modeling of sensitivity analysis can evaluate different scenarios. Growers are concerned about the production costs of pesticide control. In this study, factors include: changes in the price of pesticides, changes in pesticide application rates, or technological improvements in the mortalities of products. If one or some of these factors change, growers hope to know whether the original solution is still the best or not. Sensitivity analysis can help them determine how much each added dollar of pesticide cost is worth.

4.2 Methods

As in the real world, theoretically, maximum profit is pursued by all manufacturers and producers. Cost minimization is one way to reach the goal. An LP model was used as an analytical tool to determine an appropriate combination of pesticides and identify the economically optimal production cost of impatiens in greenhouse.

4.2.1 General Objective Function.

The problem is to determine optimal schedules for pesticide applications for each week and evaluate the production cost. It is typical to assume use of one application per week, which might include multiple products to control a range of pests and diseases. The typical production cycle of impatiens in a greenhouse is about 8 weeks, and growers typically do not apply any pesticides in the eighth week. Thus, the cost component of the model involves a minimization of pesticides for 7 weeks and their per application cost. The general mathematical programming model was defined as Equation 1.

$$\text{MinCost} = \sum_{i=1}^{12} \mathrm{P_i\,Q_i\,X_{i-j}}$$

$$=P_1Q_1\,X_{1\text{-}1} + P_2Q_2\,X_{2\text{-}1}+ P_3\,Q_3X_{3\text{-}1}+\ldots\ldots+ P_{12}\,Q_{12}Xs_{12\text{-}1}$$

$$+P_1Q_1X_{1\text{-}2} + P_2Q_2\,X_{2\text{-}2} + P_3\,Q_3\,X_{3\text{-}2} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}2}$$

$$+P_1Q_1\,X_{1\text{-}3} + P_2Q_2\,X_{2\text{-}3} + P_3\,Q_3\,X_{3\text{-}3} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}3}$$

$$+P_1Q_1\,X_{1\text{-}4} + P_2Q_2\,X_{2\text{-}4} + P_3\,Q_3\,X_{3\text{-}4} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}4}$$

$$+P_1Q_1\,X_{1\text{-}5} + P_2Q_2\,X_{2\text{-}5} + P_3\,Q_3\,X_{3\text{-}5} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}5}$$

$$+P_1Q_1\,X_{1\text{-}6} + P_2Q_2X_{2\text{-}6} + P_3\,Q_3\,X_{3\text{-}6} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}6}$$

$$+P_1Q_1\,X_{1\text{-}7} + P_2Q_2\,X_{2\text{-}7} + P_3\,Q_3X_{3\text{-}7} +\ldots\ldots+ P_{12}\,Q_{12}X_{12\text{-}7}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Pesticide applications are represented by $X_{i\text{-}j}$, where i represents the pesticide i and i=1, 2,…12. Thus, $X_1 \ldots X_{12}$ represents the 12 pesticides respectively (Avid = X_1, Mesurol = X_2, Ornazin = X_3, Orthene = X_4, Overture = X_5, Pylon = X_6, Conserve = X_7, Safari = X_8, Tristar = X_9, BotaniGard = X_{10}, QRD 452 = X_{11}, Met 52 = X_{12}). j represents the week in which the pesticide is applied and j=1,2, …7. $X_{1\text{-}1}$ indicates that pesticide 1 is applied at week 1, $X_{1\text{-}2}$ indicates that pesticide 1 is applied at week 2, and so on.

P_i indicates the price (dollars/oz) of pesticide i and Q_i represents the quantity of pesticide i, where i =1, 2, 3…12. The price of a pesticide (P_i) times the quantity of the pesticide (Q_i) indicates the cost of one application of the specific pesticide.

4.2.2 Decision Variables

The decision variables represent choices available to the decision maker in terms of amounts of either inputs or outputs (Chinneck, 2004). In Equation (1), X1, X2…are decision variables.

The pesticides in this LP model were chosen by growers, industry representatives, and research experts. Based on the communication with them, Avid, Mesurol, Ornazin, Orthene, Overture, Pylon, Conserve, Safari, Tristar, BotaniGard, QRD 452 and Met 52 were selected. Most, except Ornazin, QRD 452 and Met 52, are common and popular products for control of thrips in the greenhouse. The former 9 pesticides were chosen since they had proven effective on nurseries and in research experiments. QRD 452 and Met 52 are newly developed biological products and do not have mature markets yet. They are both recently approved by EPA, but not in all states (http://www.davisenterprise.com/business/agraquest-gets-epa-approval-for-requiem-insecticide/). Met 52 was registered by EPA at the end of 2010 (EPA Registration Number: 70127-10). QRD 452 (with the trademark "Requiem") was registered by EPA in 2010 (Registration Number 69592–25). A research scientist for AgraQuest (the manufacturer of QRD 452) indicated that the company decided not to seek extension of QRD 452's registration to include production of ornamental plants in greenhouse. Despite that, researchers remain interested in testing the efficacy of QRD 425.

4.2.3 Binary Variable

In a standard LP model, variable coefficients may take any fractional value. However, a binary variable is restricted to take on the values 0 or 1. This represents the selection or rejection of an option, the turning on or off of switches, a yes or no answer, or many other situations (Chinneck, 2004).

A standard form of the objective function is: Min Z= $\sum_{j=1}^{n} C_j X_j$ (C: coefficient. X: variable). All of the X_j in the above equations (where j = 1, 2, 3...n) are binary variables. All objective function coefficients are non-negative. This seems like a restrictive set of conditions, but many problems are easy to convert to this standard form. It is also easy to order them as they are integer (Chinneck, 2004).

In this specific problem, 12 pesticides and the week of application are decision variables. In the solution, several products are available for application treatment and only some, but not all, of the products will be chosen for application. Thus in this specific case, each variable is defined as a binary variable which takes on the values of 0 or 1 in the optimal solution (Equation 3). A value of 0 implies the product is not applied, while a value of 1 implies that the product is applied.

The binary variables in this project can be expressed as the following equation.

$$\sum_{i=1}^{12} \mathrm{X}_{\mathrm{i-j}} = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Here $\mathrm{X}_{1-1}, \mathrm{X}_{2-1}, \mathrm{X}_{3-1}$ …… X_{12-1} are binary.

$\mathrm{X}_{1-2}, \mathrm{X}_{2-2}, \mathrm{X}_{3-2}$ ……X_{12-2} are binary.

…….

$\mathrm{X}_{1-7}, \mathrm{X}_{2-7}, \mathrm{X}_{3-7}$ ……X_{12-7} are binary.

$\sum_{i=1}^{12} \mathrm{X}_{\mathrm{i-1}} = 1$, (i-1 means ith chemical is applied at week 1)

$\sum_{i=1}^{12} \mathrm{X}_{\mathrm{i-2}} = 1$, (i-2 means ith chemical is applied at week 2)

4.2.4 The Fully Specified Objective Function

The coefficients are the mathematical product of pesticide price and the midrange application rate (coefficient= price * rate) for each pesticide based on the label (Table 9). Label rates for pesticides applications usually are per 100 gallons of water. Based on the growers' experience, 25 gallons of pesticide mixture typically is sufficient for foliar spray of plants in one greenhouse (30 feet x 100 feet). Thus 100 gallons of mixture covers 4 standard greenhouses (approximately 12, 000 square feet).

MinCost= $6.98X_{1-1}+ 17.88 X_{2-1}+2.48 X_{3-1}+ 1.29X_{4-1}+12.96X_{5-1}+26.7X_{6-1}+17.01X_{7-1} +12.95X_{8-1}+1.44X_{9-1}+30X_{10-1}+5.86X_{11-1}+7.5X_{12-1}$ (the cost of week 1)

$+ 6.98X_{1-2} + 17.88 X_{2-2} + 2.48 X_{3-2} + 1.29X_{4-2} + 12.96X_{5-2} + 26.7X_{6-2} + 17.01X_{7-2} + 12.95X_{8-2}$

$+1.44X_{9-2} + 30X_{10-2} + 5.86X_{11-2} + 7.5X_{12-2}$ (the cost of week 2)

$+ 6.98X_{1-3} + 17.88 X_{2-3} + 2.48 X_{3-3} + 1.29X_{4-3} + 12.96X_{5-3} + 26.7X_{6-3} + 17.01X_{7-3} + 12.95X_{8-3}$

$+1.44X_{9-3} + 30X_{10-3} + 5.86X_{11-3} + 7.5X_{12-3}$ (the cost of week 3)

$+ 6.98X_{1-4} + 17.88 X_{2-4} + 2.48 X_{3-4} + 1.29X_{4-4} + 12.96X_{5-4} + 26.7X_{6-4} + 17.01X_{7-4} + 12.95X_{8-4}$

$+1.44X_{9-4} + 30X_{10-4} + 5.86X_{11-4} + 7.5X_{12-4}$ (the cost of week 4)

$+6.98X_{1-5} + 17.88 X_{2-5} + 2.48 X_{3-5} + 1.29X_{4-5} + 12.96X_{5-5} + 26.7X_{6-5} + 17.01X_{7-5} + 12.95X_{8-5}$

$+1.44X_{9-5} + 30X_{10-5} + 5.86X_{11-5} + 7.5X_{12-5}$ (the cost of week 5)

$+ 6.98X_{1-6} + 17.88 X_{2-6} + 2.48 X_{3-6} + 1.29X_{4-6} + 12.96X_{5-6} + 26.7X_{6-6} + 17.01X_{7-6} + 12.95X_{8-6}$

$+1.44X_{9-6} + 30X_{10-6} + 5.86X_{11-6} + 7.5X_{12-6}$ (the cost of week 6)

$+6.98X_{1-7} + 17.88 X_{2-7} + 2.48 X_{3-7} + 1.29X_{4-7} + 12.96X_{5-7} + 26.7X_{6-7} + 17.01X_{7-7} + 12.95X_{8-7}$

$+1.44X_{9-7} + 30X_{10-7} + 5.86X_{11-7} + 7.5X_{12-7}$ (the cost of week 7) ………………………... (3)

4.2.5 Constraints

Constraints exist because certain limitations restrict the range of a variable's possible values. A constraint of a linear program is binding at a point p if the inequality is met with equality at p. Constraints are limitations that restrict the alternative variables to decision makers (Chinneck, 2004). Usually, the constraints are inequalities like $\sum a_{ij} X_j \geq b_i$. The graphic depiction of the process for solving linear programming exercises (showing constraints) forms a walled-off area on the x,y-plane (called the feasible region, it is the set of all possible feasible solutions of the LP) (QuickMBA, 2010). Iterations find the intersection points of the various pairs of lines, and test these corner points in the formula to find the highest or lowest value. There are 5 types of constraints (McCarl and Spreen, 1997):

1. Lower and upper bounds on the values of the decision variables. For example: $x_1 \geq 10$ (lower limit); $x_2 \leq 20$ (upper limit).
2. Limitation constraints. These are often used to model limited resources, such as time, units of material, money, etc. For example: $3x_1 + 5x_2 \leq 50$ (total 50 hours are available, where product 1 requires 3 hours, product 2 requires 5 hours).
3. Requirement constraints. They are used to model a requirement which must be satisfied, such as satisfying the requirements of a contract, forcing the investment of all money in a portfolio, etc. For example: $X_1 + X_2 + X_3 = 10$ (total production must equal 10 units, in any combination of products 1, 2, and 3).
4. Ratio constraints, similar to weighted average and percentage constraints. These are used to model situations where the value of one (or more) variable, compared with the value of another (one or more), must satisfy some relationship. For examples: $X_1 / X_2 \geq 2$ (That is, the ratio of x_1 to x_2 must be at least equal to or greater than 2).
5. Balance constraints**.** These are used to model processes where the "inputs" must equal the "outputs." For example: X (input)=Y(output+ waste)

4.2.5.1 Constraints that Describe Application Limits

In this problem, based on the pesticides application labels and the suggestions of scientists, there is a maximum number of applications for most pesticides except those biological ones. The descriptions of constraints of each pesticide were listed in Table 4.1. Since the production cycle of greenhouse impatiens was around 8 weeks, most of the pesticides could not be applied more than 2 times. Experts asserted that the same product should not be applied for more than 2 consecutive weeks (Table 4.2). The main reason for the latter constraint was to prevent or minimize the potential to develop resistance in thrips populations, thus prolonging the effectiveness of currently used pesticides by limiting the application times and rotating pesticides with different modes of action (Cloyd, 2010).

Some pesticides, like Ornazin, QRD 452 and Met 52, are biological pesticides. Therefore there are no application limits or maximum number of application times for them (Table 10). That is, these three products (Ornazin = X3, QRD 452 = X11, Met 52 = X12) could be applied for consecutive 7 weeks. Thus the number of i (Equation 1) was taken from 1 to 7. Labels for other pesticides typically specify 2 or fewer applications during the crop cycle. For example: $X_{1\text{-}1} + X_{1\text{-}2} \leq 2$ would indicate that pesticide 1was not allowed to be applied for more than 2 times for 2 consecutive weeks.

4.2.5.2 Application Limits for Biological Pesticides

There are several mechanisms for biological pesticides to reduce thrips damage, such as competition for nutrients and space (Elad, 1996), interference with a pathogen's pathogenicity enzymes (Kapat et al., 1998), direct interaction with the pathogen through antibiosis or parasitism (Elad and Freeman, 2002) and activation of plant disease resistance (Korolev et al., 2008). They can be applied as many times as necessary since they have slight or slow selection resistance pressure. There are no application limits on the labels of Ornazin and Met 52. The label of QRD 452 states "Do not apply more than 10 times per crop production cycle", suggesting essentially no application limit.

4.2.5.3 Application Limit Constraints to Conventional Pesticides

Applying pesticides is still the main method for controlling thrips in greenhouses, and repeated applications will eventually lead to development of resistance (Cloyd, 2010). Pesticides may affect the environment, including toxicity to non-target organisms such as wildlife, environmental contamination of soil and water, and selection of resistant pests, and

Table 4.1 Pesticide types, rate range from product label, typical price from suppliers, and price per application

Name	Type	Rate range per100 gallons of water	Price ($)	Price ($) per oz	Price ($) per application*
Avid 0.15 EC	chemical	4 to 8 oz.	595.00/gal	4.65	6.98
BotaniGard 22 WP	biological	16 to 32 oz	80.00/lb	5.00	30.00
Conserve SC	chemical	8 to 20 oz	155.50/qt	4.86	17.01
Met 52 EC	biological	0.75 to 1.5 lb	20.00/lb	1.25	7.50
Mesurol 75WP	chemical	0.5 to 1 lb	190.65/2lb	5.96	17.88
Ornazin 3% EC	biological	8 to10 oz	34.70/qt	1.10	2.48
Orthene 75% SP	chemical	2 to 6 oz	1.29/oz	1.29	1.29
Overture 35WP	chemical	0.25 to 0.75 lb	103.66/ lb	6.48	12.96
Pylon	chemical	2.6 to 5.2 oz	439.00/pt	27.40	26.70
QRD 452 EC	biological	64 to 128 oz	45.00/gal	0.35	5.86
Safari 20 SG	chemical	4 to 8 oz	103.54/12oz	8.63	12.95
Tristar 30 SG	chemical	0.25 to 0.5 lb	15.40/lb	0.96	1.44

SP: soluble powder, WP: wettable powder, SC: suspension concentrate, EC: emulsifiable concentrate, SG: soluble granular

*Pesticide labels often specify a mixture based on 100 gallons of water, which covers 4 greenhouses. Therefore, the price per application per greenhouse is the 100 gallon mix divided by 4. As an example, the midrange rate for Avid is 6 oz, price per oz is $4.65. Thus 6 *4.65/4=6.98.
.

Table 4.2 Pesticide types, relative efficacy of mortality, application limits from product label and suggested constraints

Name	Type	Mortality percentage	Application limits	Constraints
Avid 0.15 EC	chemical	59.8	No more than four applications per year. 5-7 days apart	App. Time ≤ 2
BotaniGard 22 WP	biological	48.0	No more than 2 times per season, 7-10 days apart	App. Time ≤ 2
Conserve SC	pesticide	69.7	No more than 6 times in a year, never apply more than 3 consecutive application	App. Time ≤ 1
Met 52 EC	biological	24.2	No limit	No limit
Mesurol 75WP	chemical	58.5	No more than 2 times per year. At least 10 days apart.	App. Time ≤ 1
Ornazin 3% EC	biological	43.5	No limit	No limit
Orthene 75% SP	chemical	37.2	No more than 2 times per year	App. Time ≤ 1
Overture 35WP	chemical	52.9	No more than 3 times per cropping cycle or more than 3 times per 6 months	App. Time ≤ 2
Pylon	chemical	59.02	No more than 2 consecutive apps, 3 per season	App. Time ≤ 2
QRD 452 EC	biological	22.1	No more than 10 times per crop production cycle	No limit
Safari 20 SG	chemical	66.6	No more than 2 times during a two-month period	App. Time ≤ 2
Tristar 30 SG	chemical	60.1	No more than 5 applications per year. Do not reapply more than once every 7 days	App. Time ≤ 2

Note: source of relative efficacy of mortality is IR4. Application limits are obtained from the labels of pesticides.
SP: soluble powder, WP: wettable powder, SC: suspension concentrate, EC: emulsifiable concentrate, SG: soluble granular.

human health (Pimentel et al., 1992). Thus, there is an interest in reducing pesticide use. The direct way is to reduce pesticide application times and rates. The application limitation for each pesticide stated on the label was listed in the “application limits” column and the constraint for each pesticide was set in “constraints” column (Table 4.2). For example, the application limits of Avid in label was “Avid is limited to no more than four applications per year”. The constraint for Avid was less than or equal to 2 times during the two- month production cycle. The reasons for this were: (1) the production cycle of impatiens is around two months, and the product might be needed for other crops, and (2) rotations of pesticides could slow the evolution of resistance over a wider range of conditions and control insects cost-effectively (Raymond et al. 2007). The application constraint of Conserve is set as equal to or less than 1 time (Table 4.2). Experiments demonstrated that Conserve had residual activity up to 16 days, depending on temperature and the amount of sunlight (http://www.2ndchance.info/fleas-spinosadGarden.pdf). Thus Conserve could provide an extension of pest and disease control. Growers commented that Conserve is usually applied at the seventh week. Thus, it also could protect impatiens during the retail period. In a similar way, the application constraints were set for other non-biological products.

4.2.5.4 Constraint Equations for Pesticide Application Limits

Avid (X1): $X_{1-1} + X_{1-2} + X_{1-3} + X_{1-4} + X_{1-5} + X_{1-6} + X_{1-7} \leq 2$

Mesurol (X2): $X_{2-1} + X_{2-2} + X_{2-3} + X_{2-4} + X_{2-5} + X_{2-6} + X_{2-7} \leq 1$

Ornazin (X3): biological, no limits

Orthene (X4): $X_{4-1} + X_{4-2} + X_{4-3} + X_{4-4} + X_{4-5} + X_{4-6} + X_{4-7} \leq 1$

Overture (X5): $X_{5-1} + X_{5-2} + X_{5-3} + X_{5-4} + X_{5-5} + X_{5-6} + X_{5-7} \leq 2$

Pylon(X6): $X_{6-1} + X_{6-2} + X_{6-3} + X_{6-4} + X_{6-5} + X_{6-6} + X_{6-7} \leq 2$

Conserve (X7): $X_{7-7} \leq 1$

$X_{7-1} + X_{7-2} + X_{7-3} + X_{7-4} + X_{7-5} + X_{7-6} = 0$ (This equation defines Conserve was applied at week 7)

Safari (X8): $X_{8-1} + X_{8-2} + X_{8-3} + X_{8-4} + X_{8-5} + X_{8-6} + X_{8-7} \leq 2$

Tristar (X9): $X_{9-1} + X_{9-2} + X_{9-3} + X_{9-4} + X_{9-5} + X_{9-6} + X_{9-7} \leq 2$

BotaniGard (X10): $X_{10-1} + X_{10-2} + X_{10-3} + X_{10-4} + X_{10-5} + X_{10-6} + X_{10-7} \leq 2$

QRD 452 (X_{11}), Met 52 (X_{12}): both are biological pesticides, therefore there is no limit to application.

4.2.5.5 Constraints to Assure Target Level of Mortality

The general equation which is set for percent mortality per week after pesticides application was the following equation:

$$\sum_{i=1}^{12} \mathrm{RE}_{\mathrm{i}}\, \mathrm{X}_{\mathrm{i-j}} \geq \mathrm{TM}$$

Here $\mathbf{RE}_{\mathbf{i}}$ (relative efficacy) indicates the relative efficacy of thrips mortality from individual pesticide i, and i =1, 2,…12. j indicates the week number from 1 to 7. **TM** (total mortality) indicates thrips total mortality of each week after pesticides application. The fully specified equations for each week (total 7 weeks) during impatiens production with detailed thrips relative efficacy of mortality were listed below.

The **RE** value comes from the percent mortality of each pesticide based on Ornamental Horticulture Program of Interregional Research Project #4 (IR-4) summary report (Table A.1). For over forty years, the IR-4 Project has been the major resource for supplying pest management tools for specialty crops by developing research data to support registration clearances (Thompson et al. 2006). The IR-4 Project's Ornamental Horticulture Program works with growers, researchers, registrants and regulatory agencies to assist new pesticide registrations. In addition, new diseases, insects, and weeds as well as new crops on already registered ornamental horticulture product labels are added (Thompson et al. 2006). Thus the IR-

4 Project’s Ornamental Horticulture Program helps provide safe and effective pest management solutions for greenhouse, nursery, landscape and forestry producers. For the last 5 years, the IR-4 Ornamental Horticulture Workshop has developed efficacy data on new products and currently registered products. From 2006 through 2011, about 57 products representing 48 different active ingredients were tested for thrips management. The data (in Table4.2) were the average value of the results of same pesticide reported in different experiments based on the past 6 years’ work.

4.2.5.6 Source of Mortality Information

The insecticides performance controlling WFT was the source of efficacy information (Table 4.2). Data were collected from the database of the Entomological Society of America (http://entsoc.org) and IR4 Research Summary (http://ir4.rutgers.edu/ir4_pdf /default.aspx?pdf =http://ir4.rutgers.edu/Ornamental/SummaryReports/ThripsDataSummary2011.pdf). The data were chosen from the research reports which were focused on “western flower thrips” and the hosts were ornamental plants. The insecticides were sprayed on test plants. The results across tests varied widely. These outcomes might have occurred because

- experiments were conducted in different seasons, different locations and conditions;
- the host plants differed across studies. For example, some were impatiens, some were marigold, some were gerbera and so on;
- the application rates of the same insecticide varied;
- the data were recorded on different “days after treatments”;
- the application times of insecticides in different experiments were different;
- thrips numbers were counted at different sampling parts in different tests (some were counted on the whole plant, some were counted on leaves, some were counted on flowers);

— the equations for calculating mortality were different. Most of them counted only live thrips. One way to calculate the percentage of mortality was: 1 - (thrips on treated sample/ thrips on control). The other way to calculate the percentage of mortality was: dead thrips/ (dead + live) (http://ir4.rutgers.edu/ir4_pdf/default.aspx?pdf=http:// ir4.rutgers.edu/ Ornamental /Summary Reports/ThripsDataSummary2011.pdf).

4.2.5.7 Justification of Mortality Constraints for Each Week

Chemicals for the control of WFT in greenhouse play an important role in protecting valuable ornamentals. Both proper selection of pesticides and appropriate application times have a direct effect on pest control. Pesticides may be either nonpersistent or persistent. Nonpersistent pesticides are broken down quickly after application by microorganisms or sunlight. A nonpersistent pesticide performs its control function soon after application and then is no longer active (Smith, 2005). On the contrary, the chemical structures of persistent pesticides do not change for a long time after application. They may stay on leaves or in the soil and give long-term pest control without repeated applications (Smith, 2005). Thus, persistent pesticides have a big drawback; that is, they may contaminate the environment for long period of time. Some even threaten people’s health. Another disadvantage of persistent insecticides is that resistance to persistent insecticides has occurred much more frequently than to nonpersistent insecticides. Non-persistent pesticides are less harmful to the environment because they do not build up in the environment, but they have to be applied more often to crops or plants to be effective (Vargas, 1975). According to pesticide labels, the 12 pesticides used in this program are nonpersistent pesticides. Weekly applications are needed to be effective. Therefore the mortality of each week is essential to examine the efficacy of pesticide applications in controlling thrips.

The thrips percent mortality target for each week was set at 50%. Theoretically, the percent mortality ranges from 0 to 100% for each pesticide. Usually, a high concentration of pesticide leads to high percent mortality. However, greenhouse producers are continually seeking new alternative options to control WFT in order to alleviate the prospect of thrips resistance. Furthermore, it is difficult to suppress WFT because they tend to reside in tight-enclosed areas including unopened flower buds and terminal buds, decreasing their susceptibility to insecticide sprays (Cloyd and Gillespie, 2012). Therefore it is hard to achieve 100% mortality. From Table 10, the highest percent mortality achieved was 69.7%, while the lowest mortality value was 22.1%. The midrange of mortalities of all 12 pesticides in Table 10 is 45%. In a literature review, researchers did not identify a level of mortality associated with marketability. Based on all of the above information, the percent mortality for each week is arbitrarily set at 50% in this study. The constraints were:

Constraint for week 1: $0.598X_{1\text{-}1} +0.585X_{2\text{-}1} +0.435 X_{3\text{-}1}+0.372X_{4\text{-}1} +0.479X_{5\text{-}1}+0.63X_{6\text{-}1}$

$+0.678X_{7\text{-}1}+0.648X_{8\text{-}1}+0.631X_{9\text{-}1} +0.48X_{10\text{-}1}+0.144X_{11\text{-}1}+0.207X_{12\text{-}1} \geq 0.5$

Constraint for week 2: $0.598X_{1\text{-}2} +0.585X_{2\text{-}2}+0.435 X_{3\text{-}2}+0.372X_{4\text{-}2} +0.479X_{5\text{-}2}+0.63X_{6\text{-}2}$

$+0.678X_{7\text{-}2}+0.648X_{8\text{-}2}+0.631X_{9\text{-}2} +0.48X_{10\text{-}2}+0.144X_{11\text{-}2}+0.207X_{12\text{-}2} \geq 0.5$

Constraint for week 3: $0.598X_{1\text{-}3} +0.585X_{2\text{-}3} +0.435 X_{3\text{-}3}+0.372X_{4\text{-}3} +0.479X_{5\text{-}3} +0.63X_{6\text{-}3}$

$+0.678X_{7\text{-}3}+0.648X_{8\text{-}3} +0.631X_{9\text{-}3} +0.48X_{10\text{-}3} +0.144X_{11\text{-}3} +0.207X_{12\text{-}3} \geq 0.5$

Constraint for week 4: $0.598X_{1\text{-}4} +0.585X_{2\text{-}4}+0.435 X_{3\text{-}4}+0.372X_{4\text{-}4} +0.479X_{5\text{-}4}+0.63X_{6\text{-}4}$

$+0.678X_{7\text{-}4} +0.648X_{8\text{-}4} +0.631X_{9\text{-}4} +0.48X_{10\text{-}4} +0.144X_{11\text{-}4}+0.207X_{12\text{-}4} \geq 0.5$

Constraint for week 5: $0.598X_{1\text{-}5} +0.585X_{2\text{-}5}+0.435 X_{3\text{-}5}+0.372X_{4\text{-}5} +0.479X_{5\text{-}5}+0.63X_{6\text{-}5}$

$+0.678X_{7\text{-}5} +0.648X_{8\text{-}5} +0.631X_{9\text{-}5} +0.48X_{10\text{-}5} +0.144X_{11\text{-}5} +0.207X_{12\text{-}5} \geq 0.5$

Constraint for week 6: $0.598X_{1\text{-}6} +0.585X_{2\text{-}6}+0.435 X_{3\text{-}6} +0.372X_{4\text{-}6} +0.479X_{5\text{-}6}+0.63X_{6\text{-}6}$

$+0.678X_{7\text{-}6}+0.648X_{8\text{-}6}+0.631X_{9\text{-}6}+0.48X_{10\text{-}6}+0.144X_{11\text{-}6}+0.207X_{12\text{-}6} \geq 0.5$

Constraint for week 7: $0.598X_{1\text{-}7}+0.585X_{2\text{-}7}+0.435X_{3\text{-}7}+0.372X_{4\text{-}7}+0.479X_{5\text{-}7}+0.63X_{6\text{-}7}$

$+0.678X_{7\text{-}7}+0.648X_{8\text{-}7}+0.631X_{9\text{-}7}+0.48X_{10\text{-}7}+0.144X_{11\text{-}7}+0.207X_{12\text{-}7} \geq 0.5$

4.3 Results and Discussion

Linear programming problems can be solved in SAS by using the PROC LP procedure. The LP procedure provides various control options and solution strategies. It also provides various kinds of intermediate and final solution information. SAS input data for linear programming models solved with the PROC LP procedure were entered in sparse data format. The sparse format is designed to specify only nonzero coefficients in the description of linear programs (SAS Institute Inc, 1999). Using sparse format enables the SAS program to run efficiently.

In addition to the optimal solution of a linear programming problem, evaluation of the sensitivity of the optimal solution to change in the parameters is important. Sensitivity analysis included assessing the impact on pesticide management problems if the values of these parameters were changed from current to other reasonable values. It also was used to assess the impact of changing assumptions of the model. Thus, a sensitivity analysis was used to examine how the change, such as pesticides prices and mortality constraints, would affect the optimal solution.

The output of the LP procedure consists of the following sections: (1) solution summary, (2) variable summary, (3) constraint summary, and (4) sensitivity analysis including objective function sensitivity analysis and right hand side sensitivity analysis. The following sections illustrate the results of the output.

4.3.1 Variable Summary

The results from the variable summary (Table 4.3) provide information about the variables of the problem for the optimal solution. Seven variables are listed for this problem. The ‘Status’ column identifies which variables are in the optimal solution at nonzero values. Results for this problem indicate that X9-5 is in the optimal solution. The ‘Type’ column identifies the type of each variable. All variables are binary variables in Table 4.3. Objective function coefficients for each variable are listed in the ‘Price’ column. The optimal solution for this problem is listed in the ‘Activity’ column. Here all variables have ‘1’ value in ‘Activity’ column. This indicates that the listed variables all have 1 treatment in optimal solution (those variables with 0 values in the ‘Activity’ column are not included in this table as they are not applied in the optimal solution).

The ‘Reduced Cost’ column lists the allowable increase (when maximizing) from the current value of this coefficient while remaining in the basis at the optimal solution, or the allowable decrease (when minimizing) (Hillier and Lieberman, 2001).

Table 4.3 Output of variable summary of optimizing pesticides programs linear programming for thrips control of impatiens in greenhouse

		Variable	Summary		
Variable name	Status	Type	Price	Activity	Reduced cost
X1-1		Binary	6.98	1	1.12
X1-6		Binary	6.98	1	5.69
X7-7		Binary	17.01	1	11.15
X8-3		Binary	12.95	1	7.09
X8-4		Binary	12.95	1	7.09
X9-2		Binary	1.44	1	4.57
X9-5	Basic	Binary	1.44	1	0

4.3.2 Solution Summary

The solution summary provided information about the problem solution. Important information provided in solution summary was the value of the objective function. For this particular problem, the objective function value was $59.75. This indicated that if the chosen pesticides in the solution would be applied in the indicated week, the minimum pesticides application cost for WFT control during 7 weeks for impatiens in a greenhouse was $59.75 and all constraints would be satisfied.

The variables in the optimal solution from the LP model were shown in Table 4.3. The corresponding pesticide names (variables) in the result of LP in Table 4.3 and mortality and cost per application are listed in Table 4.4. As can be seen, the results showed at weeks 1 and 6, Avid was applied; at week 2 and 5, Tristar was chosen; at week 3 and 4, Safari was selected. Conserve was selected for week 7. The application costs of Avid, Tristar, Safari and Conserve provided the minimum cost solution for this specific problem. The objective function value using the LP procedure for WFT control for impatiens per greenhouse was $59.75 when the mortality constraints of each week were at least 50%. From Table 4.4, it showed that each pesticide had a mortality which was greater than 50%, as required by mortality constraints. If the mortality of the chosen pesticide was less than 50%, then it could not have been chosen by the model. Thus

Table 4.4 Product symbols and names, mortality and price per application from the linear programming solution in Table 4.3

Week	Product symbol	Product name	Mortality	Price per application($)
1	X1-1	Avid	0.598	6.98
2	X9-2	Tristar	0.601	1.44
3	X8-3	Safari	0.666	12.95
4	X8-4	Safari	0.666	12.95
5	X9-5	Tristar	0.601	1.44
6	X1-6	Avid	0.598	6.98
7	X7-7	Conserve	0.697	17.01

the mortality was the most important factor for each pesticide in order to be chosen in the LP model.

4.3.3 Constraint Summary

The "Constraint Summary" (Table 4.5) provides information about the right hand side values of the problem in the optimal solution. In this problem, the right hand side values include mortality percentages, application limits and binary constraints. In Table 4.5, the objective function is shown in the first line and its optimal objective function value "59.75" is listed under "Activity" column. Then seven constraints that require mortality to be a given level by week are listed. The "mortality 1" constraint is the percent mortality of the pesticide for week 1 and so on. Values of the mortality constraints used at each week are listed in the "Activity' column". For example, "0.598" (row 2) in "Activity" column indicates that the percent mortality of thrips in week 1 is 59.8%. The "Dual Activity" (also known as dual price or shadow price) represents the amount the objective function value would change (increase for a maximization model or decrease for a minimization model) given a unit of increase on the right hand side of the constraint (Reeb and Leavengood, 2000). Non-zero values in the "Dual Activity" column indicate constraints which are binding or limiting the solution.

Table 4.5 Constraint summary of linear programming model to optimize pesticides programs for thrips control of impatiens in greenhouse

		Constraint Summary		
Constraint name	type	RHS	Activity	Dual activity
Cost	Objective	0	59.75	.
Mortality1	GE	0.5	0.598	0
Mortality2	GE	0.5	0.631	0
Mortality3	GE	0.5	0.648	0
Mortality4	GE	0.5	0.648	0
Mortality5	GE	0.5	0.631	0
Mortality6	GE	0.5	0.598	0
Mortality7	GE	0.5	0.678	0

In Table 4.5, the dual prices of all mortality constraints of each week are zero. Binding constraints are constraints that hold with equality at the optimal solution. Any change to the right hand side of a binding constraint will change the optimal solution. Any change to the right hand side of a non-binding constraint will cause no change in the optimal solution (Reeb and Leavengood, 2000). Therefore the zero dual prices in Table 4.5 indicate that these constraints are all non-binding constraints.

4.3.4 Sensitivity Analysis

Sensitivity Analysis concerns how the solution derived from the model would change if the value assigned to the parameter were changed to other possible values (SAS Institute Inc, 1999). The two most important parameters which were evaluated are objective function coefficients and the right hand side values.

4.3.4.1 Objective Function Coefficients (same meaning as price in SAS output) Sensitivity Analysis

The RANGEPRICE option is used with LP procedure to analyze the sensitivity of the solution to changes in the objective function. The SAS program statement could be written as follows:

```
PROC LP SPARSEDATA  RANGEPRICE;
```

Sensitivity analysis of the objective function coefficients provides the range over which each parameter could vary while leaving the optimal solution (values of decision variables) unchanged (Salassi, 2004). The linear programming procedure reported the coefficient range analysis for each variable in every week. All pesticides could be sensitive to any coefficients' changes in their decision variables, thus affecting total value of objective function. For each pesticide, when their objective function coefficients (cost per application) were within the allowable range, the optimal objective function value does not change. The results of Table 4.6 indicated the range of unit cost increase for each decision variable that would not change the optimal solution, while the value of objective function would change if coefficients change.

From Table 4.4, the current optimal solution to the linear programming model is Avid, Tristar, Safari and Conserve. The range of each objective function coefficient provides the range of values over which the current solution will remain optimal. The current contribution to minimum cost of objective function is $ 6.98 per application cost of Avid, $1.44 per application of Tristar, $12.95 per application of Safari and $17.01 per application of Conserve. It is obvious that an increase in the pesticide application cost would lead to increased production cost of greenhouse impatiens.

For each decision variable, the upper and lower ranges of the production cost (objective function coefficient) are shown in Table 4.6. "minimum phi" (or "maximum phi") indicates the minimum (or maximum) value for which the basic variables remain basic. The "price" column gives the minimum (under the section labeled minimum phi) or maximum (under the section labeled maximum phi) value of the coefficient. The "Objective" column gives the objective function value. The "Entering" column indicates the entering variable. The entering variable identifies the variable whose reduced cost first goes to zero as objective function value reaches its minimum or maximum. This is the nonbasic variable that would enter the basis to maintain optimality (SAS Institute Inc. 1999).

Table 4.6 showed the range over which the current basic solution remained optimal so that the current pesticide program need not change. For example, in Table 4.6, the coefficient value of X1-1 at week 1 could vary anywhere between $5.86 and infinity (originally at $6.98) and the optimal solution would remain unchanged. Below $5.86, the optimal solution will change. Similarly, the value of X1-6 at week 6 could vary anywhere between 1.29 (Though pesticide is the same, the lower bound of X1 at week 6 is $1.29. It is different from $5.86 at week 1. The reason is that X1 is treated as different subject at different week) and infinity (originally at $6.98); the value of X8 at week 3 and 4 could vary anywhere between $5.86 and infinity (originally at $12.69); the value of X9 at week 2 could vary anywhere between -3.13 (the computer calculation generates a negative number that satisfies to the condition. Since the price of a purchased input could not go below 0, the minimum value would be 0. In mathematics, -3.13 is a number and the equation is satisfied) and infinity (originally at $1.44); the value of X9 at week 1 could vary anywhere between -1.94 and infinity (originally at $1.44) and the value of X7 could vary from $5.85 to $17.01(originally at $17.01).

Table 4.6 Sensitivity analysis of objective function coefficients from the linear programming model for thrips control of impatiens in greenhouse

Input Price Range Analysis						
Variable	Minimum phi			Maximum phi		
name	Price	Entering	Objective	Price	Entering	Objective
X1-1	5.86	X1-1	58.63	Infinity	.	Infinity
X1-6	1.29	X1-6	54.06	Infinity	.	Infinity
X7-7	5.86	X7-7	48.60	Infinity	.	Infinity
X8-3	5.86	X8-3	52.66	Infinity	.	Infinity
X8-4	5.86	X8-4	52.66	Infinity	.	Infinity
X9-2	-3.13	X9-2	55.18	Infinity	.	Infinity
X9-5	-1.94	X3-5	56.37	Infinity	.	Infinity

Note: Price column indicates up or low (under Maximum or Minimum phi section) bound.

In addition, the output in Table 4.6 showed that if the cost of X1-1 decreased from $6.98 to $5.86, the objective function value (total cost) would decrease from $59.75 to $58.63. This is reasonable as decreasing the pesticide cost leads to decrease the production cost. It would become optimal for any fractional decrease in the cost of a pesticide. When the original price of X1-1 was $6.98, the reduced cost of X1-1 was 1.12 (Table 4.4). Therefore decreasing the unit cost of X1-1 from $6.98 to $5.86 would drive its reduced cost to zero (1.12-1.12 = 0). Any further decrease would drive its reduced cost to negative and would result in an alternative optimal solution. At this point ($5.86) where the reduced cost is zero, the objective function value would be $58.63 (59.75 -1.12). This value matched the results in Table 4.6. Similarly, if the cost of X9-5 were to decrease from $1.44 to -$1.94 (originally at $1.44, reduced cost is zero), the unit change was 3.38 (1.44 – (-1.94) =3.38). The objective function value would change to 56.37 (59.75-3.38 = 56.37). This procedure applies to all other variables.

Therefore, output 4.6 showed the range over which the current basic solution remained optimal so that the current pesticide use program need not change. Between the interval of minimum phi and maximum phi, the optimal solution would not change no matter what value the coefficient takes. Outside the lower and upper bound, the optimal objective function value would change. That is, the current production program would switch to other pesticide schemes because the combination of pesticides (in Table 4.4) would not provide an optimal solution. As pointed out above, the value of objective function would change if objective function coefficients change, but the optimal solution would not change if the coefficients remain in their allowable range.

In Table 4.6, the lower bound of X1 at week 1 was $5.86. The original price of X1 was $ 6.98. The difference between them was $1.12. Similarly, the difference of X1-6 between the lower bound and original price was $5.69. The difference of X7-7 between the lower bound and original value was $11.15. The difference of X8-3(/X8-4) was $7.09. To X9-2 and X9-5, the difference was $4.57 and $3.38 respectively. Thus, the lower bound of X1-1 was the closest to its original price. The lower bound of X7-7 was the farthest to its original price. Therefore, X1-1 might be more sensitive than the others since its original value was the nearest to the lower bound and X7-7 might be the least sensitive one since its original price was the farthest to the lower bound. As pointed out before, the interval of the lower bound and upper bound provided how much the coefficient could change without changing the optimal solution. A decision maker might be concerned about whether the optimal solution was sensitive to a small change in one of the original coefficients of the objective function (or the right hand side constraints). For example, is the optimal solution sensitive to a price change of X1-1 from $6.98 to $5.98? Based on Table 4.6, the optimal solution appeared more sensitive to a price reduction of X1-1than to the coefficients of the other variables because the lower bound is rather close to coefficient value This kind of examination of impact of the original price on the output results was important for a decision maker since he might be interested in the impact of market variations in the cost of insecticides.

4.3.4.2 Right Hand Side Sensitivity Analysis

Right hand side values normally represent a limitation on a resource. Resources change as business and marketing conditions change (Hillier and Lieberman, 2001). Sensitivity analysis of the right hand side values provides information on how the optimal solution will change if right hand side values change. The RANGERHS option is used with LP procedure to analyze the sensitivity of the solution to changes in right hand sides of constraints. The SAS program statement could be written as follows:

```
PROC LP SPARSEDATA  RANGERHS;
```

Table 4.7 showed the results of right hand side sensitivity analysis. The “leaving” column identified the leaving variable. The leaving variable indicated the basic variable that first reaches either the lower bound or the upper bound as the objective function value reaches its minimum.

This was the basic variable that would leave the basis to maintain primal feasibility (SAS Institute Inc. 1999).

The right hand side sensitivity analysis provided the range over which each right hand side value could vary while the optimal solution remained unchanged (Salassi, 2004). Thus when we change each mortality constraint by one unit (one percent) in the allowable range (right hand side value), the optimal solution remained feasible. For example, in the problem presented in Table 4.7, the percent mortality of week 1 (originally at 0.5) could vary anywhere between infinity (0, non-negative constraint value) and 0.598 and the current optimal solution would remain feasible. Outside of this range, pesticide combinations of each week were not feasible because one or more of the model constraints would be violated.

Table 4.7 Sensitivity analysis of right hand side value from the linear programming model for thrips control of impatiens in greenhouse

	RHS range analysis					
Variable name	Minimum phi			Maximum phi		
	RHS	Leaving	Objective	RHS	Leaving	Objective
Mortality1	infinity	.	.	0.598	mortality1	59.75
Mortality2	infinity	.	.	0.631	mortality2	59.75
Mortality3	infinity	.	.	0.648	mortality3	59.75
Mortality4	infinity	.	.	0.648	mortality4	59.75
Mortality5	infinity	.	.	0.631	mortality5	59.75
Mortality6	infinity	.	.	0.598	mortality6	59.75
Mortality7	infinity	.	.	0.678	mortality7	59.75

As discussed in the previous section, the shadow price associated with a particular constraint was the change in the optimal value of the objective function per unit increase in the right hand side value for that constraint, all other problem data remaining unchanged (Reeb and Leavengood, 2000). For our example, the shadow prices were 0 dollars per unit of production cost (Table 4.5). As the shadow prices were associated with the constraints of the problem, but not the variables, the value of shadow price indicated the marginal change of an additional unit of a particular right hand side value (Reeb and Leavengood, 2000).

The original assumption of mortality of each week was 0.5. The difference between the upper bound and the original value of mortality 1 was 0.098. Similarly, the difference of mortality 7 was 0.178. Thus mortality 1 was more sensitive than the others since it had the smallest range between the original and upper bound of right hand side. As mentioned before, the percent mortality of each pesticide was the average value of the experimental data from IR-4. The value might have a wide variability since the collected data were affected by the number of observations, the sampling parts and plants and thrips calculation equations. Therefore, a decision maker may be more confident about the result when th outcome was based on more observations. Based on the sensitivity analysis, a decision maker could determine which data had a significant impact on the results and concentrate on getting a more reliable data for that item.

In summary, in this study, the optimal solution for pesticides application strategy for each week is: Avid is applied at weeks 1 and week 6. Safari is applied at weeks 3 and 4. Tristar is applied at weeks 2 and 5. Conserve is applied at week 7. This strategy leads to the minimum production cost of impatiens in greenhouse which is $59.75 for total 8 weeks' cycle.

This linear programming model is based largely on product prices, application rates, and incorporates a weekly mortality requirement. The schedule changes as the prices of pesticides and application inputs change, and this could also influence a decision on WFT management.

4.4 References

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Chapter 5. Summary and Implications

5.1 Summary of Research Problem

Pests continue to damage ornamental plants and crops. Thrips (mainly western flower thrips, *Frankliniella occidentalis*) were ranked among the top three arthropod pests (with two spotted spider mite and aphids) for three consecutive years from 2006 to 2008 (IR-4 Ornamental Research Priority Summary, 2008). WFT is one of the most serious pests in the ornamental industry (Lewis, 1997). It is a common pest on almost all crops, causing a wide range of crop damage due to its feeding pattern (Lewis, 1997). The direct damage to crops includes surface blemishes, distorted growth, sunken tissues on leaf undersides, and deformation of flowers (Van Dijken, 1994). The indirect damages include pathogens easily invading plants through the feeding wounds created and transmitting plant viruses (tomato spotted wilt virus and impatiens necrotic spot wilt virus) to other crops (Terry, 2010).

Impatiens is one of the most popular warm-season bedding plants in the U.S. Based on USDA's survey data, the wholesale value of impatiens in the U.S. was around $153 million in 2008 (USDA, NASS, 2008).

The general objective of this project was to estimate the production cost of an optimal WFT control strategy. The specific objectives of this research were: (1) to identify thrips control options for impatiens (alternative impatiens WFT control programs, including biopesticides used alone, in combination, and conventional products alone) and to estimate the production cost of each scheme; (2) To determine optimal thrips control programs using linear programming procedures.

A partial budget method was implemented to estimate the change of production cost that would occur from each of 6 control strategies on impatiens in the greenhouse. The components of these partial budgets included fertilizer, labor, scouting, fuel and pesticide costs. The sum of the five costs provided the total production cost of each strategy. Thus the effect of each item and the changes of production cost were determined.

The linear programming methodology was implemented to identify pesticides that minimized cost and satisfied production system constraints of impatiens in a greenhouse. To make the linear programming model more useful, sensitivity analysis was performed.

5.2 Partial Budget Results Summary

Six pesticide schemes were designed by using conventional pesticides or biopesticides to estimate production cost of thrips control on impatiens in greenhouse production. A partial budget analysis was conducted to evaluate the cost of the six pesticide schemes. The components of these partial budgets included fertilizer cost, labor costs, pesticides cost and fuel cost. Among them, strategies 3, 4 and 5 were the schemes to compare costs of QRD 452 and Met 52. Strategies 1, 2 and 6 were schemes commercially available in the market.

The results showed that strategy 6 had the highest total production cost ($197.44). Strategy 5 had the second highest cost which was $180.75. Strategies 3, 4 and 5 were similar in total production cost, which were $174.83, $175.02 and $175.12, respectively. The total production cost of strategy 2 was $162.96. Strategy 1 had the lowest total cost ($153.28). The difference between strategies 1 and 6 was $44.16. Strategy 2 used least pesticides and had the lowest pesticide cost ($26.27) among the 6 strategies. Strategy 2 was the only scheme containing scouting cost. The scouting cost in strategy 2 was $73, which accounted for 44.8% of the total production cost. Scouting offset part of the pesticides cost, labor cost and fuel cost.

Strategy 6 had the highest pesticides cost among the 6 programs as BotaniGard is more expensive than any other in the group. Compared to conventional pesticides, biopesticides, such as BotaniGard, Met 52 and QRD, have a higher market price. Thus, the schemes containing biopesticides usually have a higher total production cost than those only applied with nonbiopesticides.

The partial budget procedure showed the main factors influencing the total cost were the cost of labor, pesticides cost and fertilizer. Among them, labor cost was the most important component since it had a high percentage in total cost. These strategies could reduce or control WFT populations to levels that allow greenhouse producers to grow and sell a high quality crop with minimal aesthetic injury. Thus, partial budget analysis could provide decision makers with additional information with which to make more informed decisions regarding production cost and revenue.

5.3 Linear Programming Results Summary

The optimal WFT control program for pesticide applications on impatiens in a greenhouse was based on the assumption that thrips mortality must be at least 50% for each week. Avid was applied at week 1 and week 6. Safari was applied at weeks 3 and 4. Tristar was applied at weeks 2 and 5. Conserve was applied at week 7. This strategy led to the minimum pesticide cost of impatiens in a greenhouse, which was $59.75. This linear programming model was based largely on product prices and application rates, and incorporated a weekly mortality constraint which, in reality, could differ among growers and locations. Thus, this schedule would change as the prices of pesticides and application inputs change, and this could also influence a decision on WFT management. The results highlight the importance of strategic choices for growers.

5.3.1 The cost scope of partial budget and linear programming

In partial budget analysis, the range of total production costs of the six strategies was from \$153.28 to \$197.44 and the range of the pesticide costs was from \$26.27 to \$81.43. The optimal solution from the LP model indicated that the minimum cost was \$59.75, which was within the range of pesticide costs calculated in the partial budget. The LP solution was higher than the pesticide costs of strategies 1 and 2 and very close to the pesticide costs of strategies 3, 4 and 5. The lowest pesticide cost scheme was from grower strategy 2, where growers did not apply pesticides in the first four weeks but scouted daily to monitor the thrips situation. Pesticides were applied only at weeks 5 and 6. Thus, the lowest pesticide cost was obtained from this strategy. The optimal pesticide cost (\$59.75) from the LP model was higher than pesticide costs of grower strategies (1 and 2) from the partial budget. The reasons were that in the LP model, the optimal scheme was not only concerned about cost, but also minimizing thrips resistance. Also, the number of permitted applications, the pattern of consecutive applications and minimum mortality constraints restricted the optimal scheme. Growers might choose only the cheapest scheme but not the least resistant scheme. The optimal scheme was not the lowest cost, but might reduce the environmental cost and help with the resistance issue.

The linear programming procedure also conducted an objective function (price) range and right hand side range (constraints) sensitivity analysis for the optimal WFT control program. For objective function sensitivity analysis results, results indicated that the cost for Avid for week 1 (or for week 6) could vary from \$5.86 to infinity (\$1.12 to \$6.98) and the optimal solution would remain unchanged. Results for Conserve indicated that its cost could vary from \$5.86 to infinity and the optimal solution would remain unchanged. Results for Safari indicated that its cost could vary from \$5.86 to infinity and the optimal solution would remain unchanged.

Results for Tristar indicated that its cost could vary from 0 (non-negative value) to infinity, and the optimal solution would remain unchanged. Results from the right hand side sensitivity analysis provided showed that the mortality of each week could vary anywhere between infinity (0, non-negative constraint value) and the percent mortality of each pesticide and the optimal solution would remain unchanged.

This analysis provides a starting point for quantitative input to the production cost over future WFT management in greenhouse. However, the strategies considered here represent only WFT control in greenhouse impatiens. These results can be used as a stepping stone to further economic analyses of alternative thrips management strategies in this field, as well as others.

4.3 Implications

The fundamental issue in the USDA/PMAP grant that funded this project was the problem of increasing resistance to conventional pesticides that had provided effective control of WFT and other pests on ornamental plants including impatiens. Impatiens is economically important as one of the top three warm-season bedding plants. WFT and other pests consistently caused substantial losses to the nursery industry. The principal method used to deal with thrips in greenhouses was conventional pesticide applications, sometimes at high rates of frequency. This contributed to resistance, possible plant injury, and environmental contamination.

The primary way to prevent or minimize development of resistance and to prolong the effectiveness of currently available insecticides is a rotation of insecticides with different modes of action (Cloyd, 2010). Given the goal of the PMAP project, alternative, biologically-based WFT control strategies that combined resistant cultivars, levels of available plant foods (nitrogen and phosphate), and biopesticides, were evaluated as production systems. Figure 1 (Chapter 2) provides a schematic view of a plan to evaluate these relationships, and to incorporate impacts on plant quality. From these experimental results, no difference was found between the resistant and susceptible cultivars. Both nitrogen and phosphorus affected thrips population on impatiens. The biopesticides QRD 452 and Met 52 were evaluated and appeared effective in reducing thrips populations after application. However, comprehensive experiments leading to results that revealed quality differences among plants produced using the strategy branches from the tree in Figure 1 were not part of the experimental strategy adopted by the grant investigators.

This cost analysis contributes to understanding of the relationships between costs, resistance and grower motivations, and complements the objectives of the PMAP grant work. Partial budgets were based on three strategy approaches: (i) research of experts in the field who have proposed control strategies based on the need for alternative modes of action; (ii) two commercial grower control strategies, and (iii) assumed use of the biopesticides. Important results and implications are discussed below.

5.4.1 Biopesticide Strategies

These products potentially are effective. They work in different ways and work slower than conventional pesticides. Met 52 and QRD 452 are registered and have been in use for some time in European countries, but information about efficacy and plant quality was not located for this study. The mode of action is growth of spores, so reproduction to levels sufficient to control insects is required. Growers interviewed were not familiar with biopesticides or the way they work. The price strategies of companies producing these biopesticides appears to be based on the assertion that these are premium products that have unique attributes in terms of deferring resistance and offering environmental benefits. However, prices used for these calculations were based on one or two observations, or were taken from manufacturer representatives who gave anticipated prices. These prices might decline when they are in competition with other control product strategies. Partial budgets indicated these strategies are higher cost compared to the conventional product strategies.

5.4.2 A Research-based Strategy

The researcher-recommended strategy was from Cloyd (2010), who suggested rotation strategies based on using pesticides with different modes of action. One was chosen as a typical WFT control scheme and was analyzed by using partial budgeting (strategy 6 in Chapter 3). The scheme was as follows: BotaniGard (weeks 1 and 2); Pedestal (weeks 3and 4); Orthene (weeks 5 and 6); and Conserve (week 7). Each pesticide was applied once per week over a two-week period, then a new pesticide with a different mode of action was used. The consecutive two-week (or three weeks period) use of one insecticide was based on the assertion that intense use of one pesticide within one pest generation would suppress the population, and the selection pressure would be counteracted in the next generation by the use of an alternative pesticide (Broughton and Herron, 2007). This scheme was effective in controlling thrips with biopesticide and nonbiopesticide combinations in greenhouses. This scheme included BotaniGard, which was the most expensive among all pesticides considered. BotaniGard was suitable for the early stages and light population of pest control. This strategy had the highest pesticide cost and total production cost among the 6 programs.

5.4.3 Grower Strategies

Strategy 1was based on popular conventional pesticides, and had the lowest cost among the strategies budgeted (Chapter 3). The same pesticides were rotated at weeks 2, 6 and 3, 7 respectively. No pesticide was used in the first week. These pesticides had a low cost which contributed to the lowest production cost of all strategies. Growers are expected to consider cost first when they choose a scheme. The mixture of two pesticides was applied once each week, a common industry practice. Growers might use mixtures to control more than one target pest, and perhaps to better control particular pests. Given that multiple pesticides were in the mixture, the strategy's position of lowest cost was not expected. This scheme also was attractive since it reached the thrips control goal by rotating the conventional pesticides. The recommended rotation practice may suggest that growers are aware of the resistance issue and are acting to address the problem.

The second strategy included scouting, maintaining clean areas around greenhouses, and a shorter production period based on a specialized market. The second strategy used a smaller quantity of pesticides, but was not least cost among the budgeted strategies. However, scouting was included as a specific activity by managers and was given a cost. Managers probably did not view the scouting activity as separate from their routine activities, and would not count the scouting activity as a separate cash cost against the crop income. Scouting is an important way to determine numbers of thrips in the greenhouse, and could be used to forecast diseases and assess the effectiveness of management strategies (Cloyd, 2010). Production cost from partial budgeting of the scouting strategy was second lowest among the six strategies. This strategy would have the least environmental impacts among the 6 strategies since it used the smallest quantity of pesticides, and it reduced or prevented the development of resistance due to the fewer pesticide applications and cultural control.

5.4.4 Minimum Cost Strategy from the Linear Program

The set of pesticides in the solution from linear programing did not include biopesticides. The critical issues were both cost and efficacy. Cost based on price per unit was noted. Rates of biopesticide application were larger compared to conventional pesticides. Such a comparison may be irrelevant because biopesticide efficacy rates were far below the threshold used in the program. Differences in rates of mortality reported in IRAC summaries do not seem to be consistent with use of these products in other countries, and perhaps should be re-evaluated.

5.4.5 Relationship to Results from the Linear Programming Analysis.

The linear programming solution's optimal scheme included the conventional pesticides Avid (applied at week 1 and week 6), Tristar (applied at weeks 2 and 5), Safari (applied at weeks 3 and 4) and Conserve (applied at week 7). The mortality of each pesticide in the solution was at least 50%. The application cost of this scheme provided the minimum pesticide cost for this specific problem. Use of conventional pesticides was reasonable since generally they were cheaper than biopesticides, and sufficiently effective. This optimal scheme was similar to strategy 1 in that both consisted of many conventional pesticides. The difference between them was that only one pesticide was used per application per week in the optimal scheme while a combination of two pesticides was used per application per week in strategy 1. Partial budgets indicated that strategy 1 had a pesticide cost of $46.20. This was lower than the optimal scheme because of the constraints written into the program and the relatively low price of the conventional pesticides in strategy 1. Growers might consider cost first. If the efficacy of one pesticide was not enough to suppress thrips, they might mix pesticides because it was believed that a mixture was more effective in controlling thrips and other pests than a single one. The optimal scheme could achieve the efficiency of thrips control and delay the development of resistance since they reduced the overall pesticide input compared to strategy. Therefore the optimal strategy could reduce WFT thrips population, delay the development of resistance, and allow growers to grow a high quality plant with minimum cost.

5.4.6 Environmental Implications

Although using pesticides raises agricultural productivity, repeated pesticide use may lead to resistance and environmental problems. Three actions might reduce or delay the development of resistance and /or damages:

— use less pesticides. The amount of pesticide that reaches the target pest is less than 0.1 %, and more than 99.9% of the pesticide moves into the ecosystem (Silver and Riley, 2001). Reducing the amount of pesticide was the most direct and effective way to prevent resistance and reduce water pollution and soil pollution.

— use biopesticides to replace conventional ones. Biopesticides posed fewer risks than conventional pesticides. Schemes including biopesticides were expected to reduce environmental pollutions due to their natural origin, and because they usually degraded quickly. Therefore, using biopesticides such as BotaniGard to replace conventional pesticides in a scheme could reduce soil pollution while maintaining the crops quality. It will be necessary to educate growers to learn to use biopesticides. Growers might accept biopesticides if they knew that costs of pesticides were based not only on direct product cost, but on indirect environmental and economic costs.

— use rotation programs containing pesticides with different modes of action.

5.4.7 Grower Implications

Growers were expected to be more focused on cost and profitability, with pesticide resistance and environmental impacts as secondary concerns. In the case of the scouting strategy, action was taken when a problem was spotted. At that point, a product that acted quickly was necessary to solve the problem. Biopesticides were not as useful in that situation because of the delayed response. In addition, they appear to be more expensive, as noted above.

Growers should learn to use biopesticides to comply with clean water objectives of society. An approach might be to apply the recommended rotation approach as well as using lowest recommended rate from the product label rather than higher rates such as the midpoint of the recommended range. The logic would be that with the resistance issue addressed, application rates might be lower with subsequent environmental benefits.

5.4.8 Research Implication

Use of the biopesticides considered in this research in some European countries suggests they are effective products. On the other hand, IRAC results from which mortality measures were taken for this study indicated low mortality. Biopesticides seemed not as effective as conventional pesticides. The reason might be associated with points at which mortality is measured. Conventional pesticides act quickly and results are observed in a short time frame. Biopesticides, with a different action, may require a period of several days before spore populations are sufficient to affect the pest. Thus, standard experimental approaches might obscure the effectiveness of biopesticides, and researchers should be aware of this kind of different action

The total production cost of the six strategies analyzed by partial budget and the optimal pesticide scheme developed by linear programming provides guidance to growers in choosing programs and helps them make better management decisions. This also provided growers templates on how to develop their new pest management programs based on their situations and calculate the total production cost of their new pest management programs. Findings from this project helped growers make management decisions regarding both fertilization and pesticide programs. Growers were more aware of the cost and benefits of pesticides in pest management.

5.5 Suggestions for Further Research

This study involved schemes from impatiens growers in the state of Louisiana. The results obtained in this study could be adapted by the industry to be useful across the U.S. No performance measures, such as a quality index, were included in the partial budget analysis or linear programming. In the literature review, a few researchers used grades to indicate quality, but there was little discussion of the connection between plant quality and thrips mortality. Growers and researchers need better tools to examine and manage the quality index information which can be used to measure the production benefits.

This study's focus was on the growers' point-of-view. However, since there is no large dataset, many of the results reported here are not unconstrained grower choices. To ensure that the results of this study are useful and substantial, sampling to understand grower behavior may be needed to determine acceptable commercial control strategies. Future research with data collected from both producers and researchers could improve the understanding of production and marketing situation in the ornamental industry.

5.6 References

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Appendix: Tables of Mortality and SAS output of Linear programming

Table A.1 The application rate, sampling parts, subject species and mortality of pesticides from IR4

Insecticides	Application rate (oz/100gal)	Mortality (%)	Species	Sampling Part	Average Mortality(%)
Avid 0.15 EC	7.7	72	impatiens	three leaves	59.8
	7.7	53.7	Marigold	six leaves	
	7.7	53.7	Marigold	six leaves	
BotaniGard 22 WP	32	85.7	Impatiens	whole plant	48.0
	32	47.7	Impatiens	whole plant	
	32	10.7	Marigold	six leaves	
Conserve SE	8	79.1	Gerbera	five leaves	69.7
	8	26.2	Gerbera	flower	
	6	65.8	impatiens	whole plant	
	6	61.8	Marigold	six leaves	
	11	59.6	Gerbera	whole plant	
	8	100	Gerbera	flower	
	6	88.3	Impatiens	whole plant	
	6	61.8	Marigold	six leaves	
	6	75.7	Marigold	8whole plant	
	6	95.5	Impatiens	whole plant	
	6	75.9	Marigold	8whole plant	
	8	35.7	Marigold	2 flowers	
	8	93.8	Verbena	18 leaves	
	11	56.2	Marigold	six leaves	
Met 52	29	16.2	Marigold	2 flowers	24.2
	29	58.1	Verbena	18 leaves	
	29	0.63	Marigold	six leaves	
	29	16	Gerbera	flower	
	29	29.8	Marigold	five leaves	
Mesurol	16	52.4	Gerbera	13 whole plants	58.5
	16	50.0	Marigold	five leaves	
	8	69.7	Marigold	six leaves	
	16	61.8	Marigold	six leaves	

Table A.1 continued

Insecticides	Application rate (oz/100gal)	Mortality (%)	Species	Sampling Part	Average Mortality(%)
Ornazin 3% EC	8	49±15	Gerbera	Flower	43.5
	7.8	38	Ornament	flower	
Overture	8	52.7	Gerbera	five leaves	52.9
	8	20.1	Gerbera	flower	
	8	71	Gerbera	flower	
	8	63.8	Portulaca	five flowers	
	12	56.8	Portulaca	five flowers	
Pylon	10	53.9	Gerbera	five leaves	59.02
	5	59.0	Gerbera	13 whole plants	
	10	70.4	Gerbera	13 whole plants	
	2.6	56.0	Impatiens	whole plant	
	5.2	58.9	Impatiens	whole plant	
	10.4	47.0	Impatiens	whole plant	
	5	71.6	Impatiens	whole plant	
	10	87.8	Impatiens	whole plant	
	10	24.3	Portulaca	five flowers	
	5	61.3	Portulaca	five flowers	
QRD 452 EC	0.16	18	Daisy	flower	22.1
	290	34	Daisy	flower	
	128	14.4	Marigold	six leaves	
Safari	8	95	Gerbera	flower	66.6
	8	66.8	Impatiens	three leaves	
	8	32.6	Marigold	five leaves	
	8	71.9	Rose	five flowers	
Tristar 30 SG	2.26	81.1	Marigold	six leaves	60.1
	3.39	74.3	Marigold	six leaves	
	8	36.8	Gerbera	whole plants	
	2.26	81.1	Marigold	six leaves	
	3.39	74.3	Marigold	six leaves	
	3.39	85.2	ornament	leaves	
	8	47.2	Marigold	eight plants	
	8	47.2	Marigold	eight plants	
	3.39	21.7	Portulaca	five flowers	
	3.39	47.8	Rose	five flowers	
	3.39	64.6	Ornament	leaves	

Table A.2 Solution summary SAS output from linear programming

Solution Summary Integer Optimal Solution	
Objective Value	59.75
Phase 1 Iterations	11
Phase 2 Iterations	9
Phase 3 Iterations	23962
Integer Iterations	8923
Integer Solutions	23
Initial Basic Feasible Variables	26
Time Used (seconds)	3
Number of Inversions	4596
Epsilon	1.00E-08
Infinity	1.797693E308
Maximum Phase 1 Iterations	100
Maximum Phase 2 Iterations	100
Maximum Phase 3 Iterations	99999999
Maximum Integer Iterations	10000000
Time Limit (seconds)	120

Table A.3 Variable summary SAS output from linear programming

Variable Summary						
Col	Variable Name	Status	Type	Price	Activity	Reduced Cost
1	X1-1		BINARY	6.98	1	1.12
2	X1-2		BINARY	6.98	0	5.69
3	X1-3		BINARY	6.98	0	1.12
4	X1-4		BINARY	6.98	0	1.12
5	X1-5		BINARY	6.98	0	1.12
6	X1-6		BINARY	6.98	1	5.69
7	X1-7		BINARY	6.98	0	1.12
8	X10-1		BINARY	30	0	24.14
9	X10-2		BINARY	30	0	28.71
10	X10-3		BINARY	30	0	24.14
11	X10-4		BINARY	30	0	24.14
12	X10-5		BINARY	30	0	24.14
13	X10-6		BINARY	30	0	28.71
14	X10-7		BINARY	30	0	24.14
15	X11-1		BINARY	5.86	0	0
16	X11-2		BINARY	5.86	0	4.57
17	X11-3	DEGEN	BINARY	5.86	0	0
18	X11-4		BINARY	5.86	0	0
19	X11-5		BINARY	5.86	0	0
20	X11-6		BINARY	5.86	0	4.57
21	X11-7		BINARY	5.86	0	0
22	X12-1		BINARY	7.5	0	1.64
23	X12-2		BINARY	7.5	0	6.21
24	X12-3		BINARY	7.5	0	1.64
25	X12-4		BINARY	7.5	0	1.64
26	X12-5		BINARY	7.5	0	1.64
27	X12-6		BINARY	7.5	0	6.21

Table A.3 Continued

Variable Summary						
Col	Variable Name	Status	Type	Price	Activity	Reduced Cost
28	X12-7		BINARY	7.5	0	1.64
29	X2-1		BINARY	17.88	0	12.02
30	X2-2		BINARY	17.88	0	16.59
31	X2-3		BINARY	17.88	0	12.02
32	X2-4		BINARY	17.88	0	12.02
33	X2-5		BINARY	17.88	0	12.02
34	X2-6		BINARY	17.88	0	16.59
35	X2-7		BINARY	17.88	0	12.02
36	X3-1		BINARY	2.48	0	-3.38
37	X3-2		BINARY	2.48	0	1.19
38	X3-3		BINARY	2.48	0	-3.38
39	X3-4		BINARY	2.48	0	-3.38
40	X3-5		BINARY	2.48	0	-3.38
41	X3-6		BINARY	2.48	0	1.19
42	X3-7		BINARY	2.48	0	-3.38
43	X4-1		BINARY	1.29	0	-4.57
44	X4-2	DEGEN	BINARY	1.29	0	0
45	X4-3		BINARY	1.29	0	-4.57
46	X4-4		BINARY	1.29	0	-4.57
47	X4-5		BINARY	1.29	0	-4.57
48	X4-6	DEGEN	BINARY	1.29	0	0
49	X4-7		BINARY	1.29	0	-4.57
50	X5-1		BINARY	12.96	0	7.1
51	X5-2		BINARY	12.96	0	11.67
52	X5-3		BINARY	12.96	0	7.1
53	X5-4		BINARY	12.96	0	7.1
54	X5-5		BINARY	12.96	0	7.1
55	X5-6		BINARY	12.96	0	11.67
56	X5-7		BINARY	12.96	0	7.1
57	X6-1		BINARY	26.72	0	20.86

Table A.3 Continued

Variable Summary						
Col	Variable Name	Status	Type	Price	Activity	Reduced Cost
58	X6-2		BINARY	26.72	0	25.43
59	X6-3		BINARY	26.72	0	20.86
60	X6-4		BINARY	26.72	0	20.86
61	X6-5		BINARY	26.72	0	20.86
62	X6-6		BINARY	26.72	0	25.43
63	X6-7		BINARY	26.72	0	20.86
64	X7-1		BINARY	17.01	0	11.15
65	X7-2		BINARY	17.01	0	15.72
66	X7-3		BINARY	17.01	0	11.15
67	X7-4		BINARY	17.01	0	11.15
68	X7-5		BINARY	17.01	0	11.15
69	X7-6		BINARY	17.01	0	15.72
70	X7-7		BINARY	17.01	1	11.15
71	X8-1		BINARY	12.95	0	7.09
72	X8-2		BINARY	12.95	0	11.66
73	X8-3		BINARY	12.95	1	7.09
74	X8-4		BINARY	12.95	1	7.09
75	X8-5		BINARY	12.95	0	7.09
76	X8-6		BINARY	12.95	0	11.66
77	X8-7		BINARY	12.95	0	7.09
78	X9-1	DEGEN	BINARY	1.44	0	0
79	X9-2		BINARY	1.44	1	4.57
80	X9-3	DEGEN	BINARY	1.44	0	0
81	X9-4	DEGEN	BINARY	1.44	0	0

Table A.3 Continued

Variable Summary						
Col	Variable Name	Status	Type	Price	Activity	Reduced Cost
82	X9-5	BASIC	BINARY	1.44	1	0
83	X9-6		BINARY	1.44	0	4.57
84	X9-7	DEGEN	BINARY	1.44	0	0
85	mort1	BASIC	SURPLUS	0	0.098	0
86	mort2	BASIC	SURPLUS	0	0.131	0
87	mort3	BASIC	SURPLUS	0	0.148	0
88	mort4	BASIC	SURPLUS	0	0.148	0
89	mort5	BASIC	SURPLUS	0	0.131	0
90	mort6	BASIC	SURPLUS	0	0.098	0
91	mort7	BASIC	SURPLUS	0	0.178	0
92	pest11	DEGEN	SLACK	0	0	0
93	pest22	BASIC	SLACK	0	2	0
94	pest42	BASIC	SLACK	0	2	0
95	pest52	BASIC	SLACK	0	2	0
96	pest62	BASIC	SLACK	0	2	0
97	pest71	DEGEN	SLACK	0	0	0
98	pest72	DEGEN	SLACK	0	0	0
99	pest82	DEGEN	SLACK	0	0	0
100	pest92		SLACK	0	0	4.42
101	pest102	BASIC	SLACK	0	2	0

Table A.4 Constraint summary SAS output from linear programming

Constraint Summary						
	Constraint Name	Type	S/S Co	Rh	Activity	Dual Activity
1	cost	OBJECTIVE	.	0	59.75	0
2	mort1	GE	85	0	0.598	
3	mort2	GE	86	0.5	0.631	0
4	mort3	GE	87	0.5	0.648	0
5	mort4	GE	88	0.5	0.648	0
6	mort5	GE	89	0.5	0.631	0
7	mort6	GE	90	0.5	0.598	0
8	mort7	GE	91	0.5	0.678	0
9	pest11	LE	92	2	2	0
10	pest22	LE	93	2	0	0
11	pest42	LE	94	2	0	0
12	pest52	LE	95	2	0	0
13	pest62	LE	96	2	0	0
14	pest71	LE	97	1	1	0
15	pest72	LE	98	0	0	0
16	pest82	LE	99	2	2	0
17	pest92	LE	100	2	2	-4.42
18	pest102	LE	101	2	0	0
19	week1	EQ	.	1	1	5.86
20	week2	EQ	.	1	1	1.29
21	week3	EQ	.	1	1	5.86
22	week4	EQ	.	1	1	5.86
23	week5	EQ	.	1	1	5.86
24	week6	EQ	..	1	1	1.29
25	week7	EQ	.	1	1	5.86

Table A.5 Sensitivity analysis of right hand side SAS output from linear programming

RHS Range Analysis						
	Minimum Phi			Maximum Phi		
Row	Rhs	Leaving	Objective	Rhs	Leaving	Objective
mort1	-INFINITY	.	.	0.598	mort1	59.75
mort2	INFINITY	.	.	0.631	mort2	59.75
mort3	INFINITY	.	.	0.648	mort3	59.75
mort4	INFINITY	.	.	0.648	mort4	59.75
mort5	INFINITY	.	.	0.631	mort5	59.75
mort6	INFINITY	.	.	0.598	mort6	59.75
mort7	INFINITY	.	.	0.678	mort7	59.75
pest11	2	pest11	59.75	INFINITY	.	.
pest22	0	pest22	59.75	INFINITY	.	.
pest42	0	pest42	59.75	INFINITY	.	.
pest52	0	pest52	59.75	INFINITY	.	.
pest62	0	pest62	59.75	INFINITY	.	.
pest71	1	pest71	59.75	INFINITY	.	.
pest72	0	pest72	59.75	INFINITY	.	.
pest82	2	pest82	59.75	INFINITY	.	.
pest92	2	X9-3	59.75	2	X11-3	59.75
pest102	0	pest102	59.75	INFINITY	.	.
week1	1	X11-3	59.75	1	X9-3	59.75
week2	1	X4-2	59.75	2	X4-2	61.04
week3	1	X11-3	59.75	2	X11-3	65.61
week4	1	X11-3	59.75	1	X9-3	59.75
week5	1	X11-3	59.75	1	X9-3	59.75
week6	1	X4-6	59.75	2	X4-6	61.04
week7	1	X11-3	59.75	1	X9-3	59.75

Table A.6 Sensitivity analysis of price range analysis SAS output from linear programming

Price Range Analysis

		Minimum Phi			Maximum Phi		
Col	Variable Name	Price	Entering	Objective	Price	Entering	Objective
1	X1-1	5.86	X1-1	58.63	INFINITY	.	INFINITY
2	X1-2	1.29	X1-2	59.75	INFINITY	.	59.75
3	X1-3	5.86	X1-3	59.75	INFINITY	.	59.75
4	X1-4	5.86	X1-4	59.75	INFINITY	.	59.75
5	X1-5	5.86	X1-5	59.75	INFINITY	.	59.75
6	X1-6	1.29	X1-6	54.06	INFINITY	.	INFINITY
7	X1-7	5.86	X1-7	59.75	INFINITY	.	59.75
8	X10-1	5.86	X10-1	59.75	INFINITY	.	59.75
9	X10-2	1.29	X10-2	59.75	INFINITY	.	59.75
10	X10-3	5.86	X10-3	59.75	INFINITY	.	59.75
11	X10-4	5.86	X10-4	59.75	INFINITY	.	59.75
12	X10-5	5.86	X10-5	59.75	INFINITY	.	59.75
13	X10-6	1.29	X10-6	59.75	INFINITY	.	59.75
14	X10-7	5.86	X10-7	59.75	INFINITY	.	59.75
15	X11-1	5.86	X11-1	59.75	INFINITY	.	59.75
16	X11-2	1.29	X11-2	59.75	INFINITY	.	59.75
17	X11-3	2.48	X3-1	59.75	5.86	X11-1	59.75
18	X11-4	5.86	X11-4	59.75	INFINITY	.	59.75
19	X11-5	5.86	X11-5	59.75	INFINITY	.	59.75
20	X11-6	1.29	X11-6	59.75	INFINITY	.	59.75
21	X11-7	5.86	X11-7	59.75	INFINITY	.	59.75
22	X12-1	5.86	X12-1	59.75	INFINITY	.	59.75
23	X12-2	1.29	X12-2	59.75	INFINITY	.	59.75
24	X12-3	5.86	X12-3	59.75	INFINITY	.	59.75
25	X12-4	5.86	X12-4	59.75	INFINITY	.	59.75
26	X12-5	5.86	X12-5	59.75	INFINITY	.	59.75
27	X12-6	1.29	X12-6	59.75	INFINITY	.	59.75

Table A.6 Continued

		Price Range Analysis					
		Minimum Phi			Maximum Phi		
Col	Variable Name	Price	Entering	Objective	Price	Entering	Objective
28	X12-7	5.86	X12-7	59.75	INFINITY	.	59.75
29	X2-1	5.86	X2-1	59.75	INFINITY	.	59.75
30	X2-2	1.29	X2-2	59.75	INFINITY	.	59.75
31	X2-3	5.86	X2-3	59.75	INFINITY	.	59.75
32	X2-4	5.86	X2-4	59.75	INFINITY	.	59.75
33	X2-5	5.86	X2-5	59.75	INFINITY	.	59.75
34	X2-6	1.29	X2-6	59.75	INFINITY	.	59.75
35	X2-7	5.86	X2-7	59.75	INFINITY	.	59.75
36	X3-1	-INFINITY	.	59.75	5.86	X3-1	59.75
37	X3-2	1.29	X3-2	59.75	INFINITY	.	59.75
38	X3-3	-INFINITY	.	59.75	5.86	X3-3	59.75
39	X3-4	-INFINITY	.	59.75	5.86	X3-4	59.75
40	X3-5	-INFINITY	.	59.75	5.86	X3-5	59.75
41	X3-6	1.29	X3-6	59.75	INFINITY	.	59.75
42	X3-7	-INFINITY	.	59.75	5.86	X3-7	59.75
43	X4-1	-INFINITY	.	59.75	5.86	X4-1	59.75
44	X4-2	-INFINITY	.	59.75	2.48	X3-2	59.75
45	X4-3	-INFINITY	.	59.75	5.86	X4-3	59.75
46	X4-4	-INFINITY	.	59.75	5.86	X4-4	59.75
47	X4-5	-INFINITY	.	59.75	5.86	X4-5	59.75
48	X4-6	-INFINITY	.	59.75	2.48	X3-6	59.75
49	X4-7	-INFINITY	.	59.75	5.86	X4-7	59.75
50	X5-1	5.86	X5-1	59.75	INFINITY	.	59.75
51	X5-2	1.29	X5-2	59.75	INFINITY	.	59.75
52	X5-3	5.86	X5-3	59.75	INFINITY	.	59.75
53	X5-4	5.86	X5-4	59.75	INFINITY	.	59.75
54	X5-5	5.86	X5-5	59.75	INFINITY	.	59.75

Table A.6 Continued

		Price Range Analysis					
		Minimum Phi			Maximum Phi		
Col	Variable Name	Price	Entering	Objective	Price	Entering	Objective
55	X5-6	1.29	X5-6	59.75	INFINITY	.	59.75
56	X5-7	5.86	X5-7	59.75	INFINITY	.	59.75
57	X6-1	5.86	X6-1	59.75	INFINITY	.	59.75
58	X6-2	1.29	X6-2	59.75	INFINITY	.	59.75
59	X6-3	5.86	X6-3	59.75	INFINITY	.	59.75
60	X6-4	5.86	X6-4	59.75	INFINITY	.	59.75
61	X6-5	5.86	X6-5	59.75	INFINITY	.	59.75
62	X6-6	1.29	X6-6	59.75	INFINITY	.	59.75
63	X6-7	5.86	X6-7	59.75	INFINITY	.	59.75
64	X7-1	5.86	X7-1	59.75	INFINITY	.	59.75
65	X7-2	1.29	X7-2	59.75	INFINITY	.	59.75
66	X7-3	5.86	X7-3	59.75	INFINITY	.	59.75
67	X7-4	5.86	X7-4	59.75	INFINITY	.	59.75
68	X7-5	5.86	X7-5	59.75	INFINITY	.	59.75
69	X7-6	1.29	X7-6	59.75	INFINITY	.	59.75
70	X7-7	5.86	X7-7	48.6	INFINITY	.	INFINITY
71	X8-1	5.86	X8-1	59.75	INFINITY	.	59.75
72	X8-2	1.29	X8-2	59.75	INFINITY	.	59.75
73	X8-3	5.86	X8-3	52.66	INFINITY	.	INFINITY
74	X8-4	5.86	X8-4	52.66	INFINITY	.	INFINITY
75	X8-5	5.86	X8-5	59.75	INFINITY	.	59.75
76	X8-6	1.29	X8-6	59.75	INFINITY	.	59.75
77	X8-7	5.86	X8-7	59.75	INFINITY	.	59.75
78	X9-1	-1.94	X3-1	59.75	1.44	X11-1	59.75
79	X9-2	-3.13	X9-2	55.18	INFINITY	.	INFINITY
80	X9-3	1.44	X11-1	59.75	4.82	X3-1	59.75
81	X9-4	-1.94	X3-4	59.75	1.44	X11-4	59.75

Table A.6 Continued

		Price Range Analysis					
		Minimum Phi			Maximum Phi		
Col	Variable Name	Price	Entering	Objective	Price	Entering	Objective
82	X9-5	-1.94	X3-5	56.37	1.44	X11-5	59.75
83	X9-6	-3.13	X9-6	59.75	INFINITY	.	59.75
84	X9-7	-1.94	X3-7	59.75	1.44	X11-7	59.75
85	mort1	-17.2449	X3-1	58.06	0	X11-1	59.75
86	mort2	-17.6448	X9-2	57.4385	20.04386	X11-2	62.37575
87	mort3	0	X11-7	59.75	6.9404517	X3-1	60.77719
88	mort4	-17.2449	X3-4	57.1978	0	X11-4	59.75
89	mort5	-17.2449	X3-5	57.4909	0	X11-5	59.75
90	mort6	-17.6448	X9-6	58.0208	20.04386	X11-6	61.7143
91	mort7	-17.2449	X3-7	56.6804	0	X11-7	59.75
92	pest11	-INFINITY	.	59.75	1.12	X1-3	59.75
93	pest22	-INFINITY	.	INFINITY	12.02	X2-1	83.79
94	pest42	-1.19	X3-2	57.37	INFINITY	.	INFINITY
95	pest52	-INFINITY	.	INFINITY	7.1	X5-3	73.95
96	pest62	-INFINITY	.	INFINITY	20.86	X6-1	101.47
97	pest71	-INFINITY	.	59.75	11.15	X7-7	59.75
98	pest72	-INFINITY	.	59.75	11.15	X7-1	59.75
99	pest82	-INFINITY	.	59.75	7.09	X8-3	59.75
100	pest92	-4.42	pest92	59.75	INFINITY	.	59.75
101	pest102	-INFINITY	.	INFINITY	24.14	X10-1	108.03

Vita

Born and raised in Wixi, China. Xiaohua Yue had lived all of her 18 years in country. Then she went to college. She earned her bachelor's degree in Food Science at Shanghai Fisheries University. After graduation, she worked in the laboratory of the university. While there, she completed a project on the film-formed properties and applications of edible chitosan films, which became her thesis project. She graduated with a Master of Science from Shanghai Fisheries University. In 2005, she entered the Food Science graduate program at Louisiana State University, and received the Ph.D.in December of 2009. She then moved to the graduate program in Agricultural Economics, and this thesis is her work on the economics of management of western flower thrips in impatiens in greenhouse production.