Optimal Pest Control in Floriculture Production of Ornamental Crops

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Introduction

Pest control is vital to producers of ornamental greenhouse crops that are subject to physical or aesthetic damage by insects. Control in these crops is distinct from most pest control models in traditional agricultural field crops. Increasingly, greenhouse producers are striving to optimally balance the application of chemical and introduced biological input controls as well as nutritional inputs to attain desired aesthetic quality levels for the output of ornamentals.[1] Because the production environment of interest is a controlled greenhouse, horticultural controls (fertilizer or irrigation) and pest controls (chemical or biological) are micromanaged at frequent time intervals. In this process, growers make important intertemporal tradeoffs among horticultural and pest controls to keep plant quality and visual levels of insects (pest or predators) at acceptable levels.[2] Our intention is to extend traditional pest control models (e.g., Hall and Norgaard; Feder and Regev; Hueth and Regev) to identify dynamically optimal chemical, biological, and cultural controls for greenhouse crops produced for their aesthetic benefits.

Pest management in greenhouse production is complicated by the ongoing restriction or elimination of pesticides by the Environmental Protection Agency through the Food Quality Protection Act and the dynamic nature of insect and plant stocks.[3] Pesticides are being regulated due to multiple concerns, including human health, pest resistance, and spillover effects on the environment. This has stimulated interest in greenhouse management programs that conjunctively use horticultural inputs, introduced biologicals, and chemicals to control stocks of pest that damage ornamentals. With dynamic insect and plant stocks, timing of pest controls plays a critical role in greenhouse pest management practices constrained by pesticide regulations. For example, producers must avoid the consecutive use of chemicals to mitigate pest resistance (Environmental Protection Agency). Moreover, when timing the introduction of predators to control plant-damaging pests during a production season, growers must consider both the size and quality of the plant at sales time and the terminal stocks of pests or introduced predators on the plants. Terminal stocks dictate the visual prevalence of insects at sales time. These and other issues provide the economic motivation to understand the dynamically optimal combination of chemicals, introduced predators, and horticultural controls in producing ornamentals for their aesthetic benefits.

Previous pest control models include Hueth and Regev, who focused on the conjunctive management of a pest with chemical and cultural controls and its associated stock of susceptibility to pesticides. Meanwhile, Feder and Regev examined insect-natural predator interactions and environmental effects in pest control. Marsh, Huffaker, and Long investigated vector-virus-plant interactions in potato production. Other optimal control models have investigated the use of simultaneous or cyclical control strategies to address antibiotic resistance (Bonhoeffer et al.; Laxminarayan; Laxminarayan and Brown) and optimal harvesting of renewable resources (Feichtinger et al.; Wirl). The above models provide decision rules and defined economic threshold levels specific to underlying assumptions. However, they do not address problems specific to floriculture production in a controlled environment, nor do they investigate the tradeoffs between chemical and introduced biological controls in establishing aesthetic threshold levels in a theoretically consistent economic framework.[4] The controlled greenhouse environment allows use of controls generally not feasible in traditional agricultural production. For example, watering and fertilizer rates are micro-managed and can be used to influence interactions among plants and insects. Further, given restrictions on pesticide use in greenhouses, introduced predators are commonly used to control greenhouse pests (Zhang and Sanderson; Hoddle, Van Driesche, and Sanderson; Van Lenteren). It is anticipated that introduced predators can be used to conjunctively control (e.g., simultaneously, cyclical) the visual presence of pests on plants and plant quality by preying on insect-pests.

The purpose of the current study is two-fold. The first objective is to develop a conceptual bioeconomic model for the floriculture industry that will lead to optimal decision rules and economic thresholds within a discrete time framework. Necessary conditions of the model identify optimal trajectories (e.g., simultaneous, cyclical, or individual control) that define decision or planning rules and economic thresholds for profit maximizing growers producing crops with aesthetic attributes. The necessary conditions also highlight intertemporal tradeoffs between aesthetic benefits and expected future net benefits of insect stocks, which have important policy implications. Optimal decision rules are important from a social perspective in that they can reduce the inefficient practice of prophylactic pesticide applications, which may exacerbate negative externalities on human health and the environment.

The second objective is to present an exploratory empirical application of the bioeconomic model, which consists of greenhouse-grown ivy geranium, *Pelargonium peltatum* (L.)'Her ex Ait (GIV), one of its major pests, *Tetranychus urticae* Koch (TU), and a potential predatory mite, *Phytoseiulus persimilis* (PP). The empirical results indicate that when conjunctively used with chemical applications, introduced predators may play an optimizing role in bioeconomic control of pest stocks on floricultural crops.

Moreover, they indicate that timing of inputs is critical in order to control terminal stocks of pests and introduced predators and yet retain plant quality. Finally, we point out this methodology is applicable to other crops that produce output with aesthetic benefits and are hindered by pest control problems.

Floriculture Bioeconomic Model

The bioeconomic model is structured to represent the greenhouse production system of a single ornamental crop, one pest, and a prey-specific predator within the planning horizon of one cropping cycle. The pest is assumed to be significant in that it can cause major damage to the ornamental plant and its visual presence dramatically diminishes the value of the plant (Sadof and Raupp). The state variables of the system are physical plant quality (distinct from quality influences induced by the visual presence of insects), a_t, insect stocks, g_t, and prey-specific predator stocks, p_t, per unit area at time t. The control variables are timing and rate of pest controls, u_{1t}, introduced biological controls, u_{2t}, and horticultural controls, u_{3t}, measured per unit area at time t.

The optimization problem consists of a concave benefit function $B(Q(a_T, g_T, p_T); Z)$ and a convex cost function $C(u_{1t}, u_{2t}, u_{3t}; Z)$, where Z represents exogenous factors in the decision process that may include marketing agreements between a grower and buyer. In the argument of the benefit function, $Q(\cdot)$ is a continuously differentiable function that represents the total quality from the joint influence of plants and visual presence of insects. It is assumed that the benefit function is nondecreasing in total quality ($B_Q \geq 0$), while the total quality function in the terminal period is nondecreasing in physical plant quality ($Q_{a_T} \geq 0$) and nonincreasing in the visual presence of pests ($Q_{g_T} \leq 0$). In addition the model includes $F(g_T,p_T)$ which represents the expected future net benefits based on the state variables at terminal time T. Here, pests carried over to upcoming production periods are expected to decrease expected net benefits ($F_{g_t} \leq 0$) and introduced predators are expected to increase net benefits ($F_{p_t} \geq 0$) in the future. The discount factor is $b = (1+d)^{-1}$ with discount rate d.

The greenhouse grower's optimization problem is

$$(1) \quad \max_{u_{1t}, u_{2t}, u_{3t} \geq 0} \{ b^T B(Q(a_T, g_T, p_T); Z) + b^T F(g_T, p_T) - \sum_{t=0}^{T-1} b^t C(u_{1t}, u_{2t}, u_{3t}; Z)\}$$

subject to the functions of plant quality, pest growth, and introduced predator growth:

$$(2) \quad a_{t+1} - a_t = f^a(a_t, g_t, p_t, u_{1t}, u_{2t}, u_{3t}), \qquad t=0,\ldots T-1;$$

$$(3) \quad g_{t+1} - g_t = f^g(a_t, g_t, p_t, u_{1t}, u_{2t}, u_{3t}), \qquad t=0,\ldots T-1;$$

$$(4) \quad p_{t+1} - p_t = f^p(a_t, g_t, p_t, u_{1t}, u_{2t}, u_{3t}), \qquad t=0,\ldots T-1;$$

initial stocks,

$$(5) \quad a_0 = a^0,\ g_0 = g^0, \text{ and } p_0 = p^0;$$

and terminal stock constraints,

$$(6) \quad g_T \leq \overline{g}, \text{ and } p_T \leq \overline{p}.$$

The grower's objective in equation (1) is to determine the level of chemical pest controls, introduced biological controls, and horticultural controls in each period that maximizes the net present value of plant production throughout the growing season. The biological functions of the model, equations (2)-(4), are designed to structure the floriculture problem, which are general enough to identify the grower's optimal planning rules and economic thresholds and to accommodate the empirical model discussed below. Initial stocks in (5) are necessary to identify unique trajectories of the state variables.

The function $B(Q(a_T, g_T, p_T); Z)$ links quality of the plant at time of sales to market prices and delineates this influence from aesthetic benefits derived from the visual presence of pests and predators. Physical plant quality at terminal time T, a_T, embodies various quality characteristics of the ornamental crop. The appropriate quality attributes may include volume (height and width), shape (form) of the plant, foliage color, and number and size of inflorescences, but ultimately depends on the target market(s) and type of ornamental crop. Distinct from plant quality, benefits from the presence of terminal stocks of insect-pests are assumed to be nonincreasing. Alternatively, benefits from the presence of terminal stocks of insect-predators can be nonincreasing or nondecreasing. Under the more conventional perspective $(Q_{p_T} \leq 0)$, high quality plants with introduced predators that are visually detected are likely to be aesthetically less pleasing than benefits of high quality plants with no insects. Under a less conventional or an "organic" perspective $(Q_{p_T} \geq 0)$, the visual presence of predator insects may be interpreted as a benefit because they control insect-pests. The economic implications arising from the visual presence of predators on plants in the terminal period will be discussed in more detail below.

The cost function $C(u_{1t}, u_{2t}, u_{3t}; Z)$ is a function of exogenous factors such as input prices, and the level of chemical pest controls, introduced biological controls and horticultural controls. Costs of chemical pest controls, introduced biological controls, and horticultural controls are assumed to be a function of purchased inputs and application costs.

The net change in plant quality, insect pests and predator stocks from t to t+1 in (2)-(4) are modeled as continuously differentiable functions, f^j for $j \in A = \{a, g, p\}$, where f_i^j represents the ith partial derivative of the jth growth function. For example, f_g^a is the partial derivative of the net change in plant quality with respect to the pest stock. Restrictions on f_i^j are: feeding by pest decreases plant quality attributes ($f_g^a<0$); pest control increases plant quality attributes ($f_{u1}^a>0, f_{u2}^a>0$); horticultural controls can increase plant quality attributes ($f_{u3}^a\geq 0$); pest control decreases insect growth ($f_{u1}^g<0$, $f_{u2}^g<0$); predators decrease pest growth ($f_p^g<0$); and pesticides can be toxic to predators ($f_{u1}^p\leq 0$). No restrictions are placed on the effects of horticultural controls on the pest or predator.[5] The functional representations in (2)-(4) assume applications of controls occur at the beginning of the period and are immediately effective.[6]

Terminal stock constraints in (6) represent an upper bound of the detectable insects on plants that growers anticipate will be acceptable to consumers purchasing ornamental plants. These depend on the type of host plant as well as the insect of interest. For example, if the plant is typically an indoor plant, then the acceptable number of pests per plant, or terminal stock conditions, is likely to be near zero. Alternatively, if the plant is purchased for outside aesthetics, desired terminal stocks may be greater than zero.[7] Moreover, the terminal stock constraints for insect stocks, $\overline{g}$, depend on the type of pest. In cases where pests are not easily visible, the terminal stock constraint may be greater than zero. In contrast, if the pests are clearly visible, then the terminal stock constraint may be nearly zero, assuming customers would not purchase plants with pests that are visible.

Identifying terminal stocks of introduced predators, $\overline{p}$, requires different management considerations relative to terminal stocks of pests. For instance, chemical pesticides used for pest control may be detrimental to predator stocks. Here, selective insecticides that target pests and not predators can be used to control pest stocks without adversely impacting predator stocks.[8] Moreover, in the event that predators are solely dependent upon pest stocks, and if terminal pest stocks are restricted to be zero, then predator stocks will disperse or crash at the terminal period. Alternatively, if a zero terminal predator stock is desirable, then pest stocks may be driven to zero prior to the terminal period to allow predator stocks time to adjust to satisfy boundary conditions.

The Lagrangian function of the discrete time optimization problem in (1)-(6) is

$$(7)\quad L= b^{T} B(Q(a_T,\ g_T,\ p_T); Z) + b^{T} F(g_T, p_T) + \sum_{t=0}^{T-1} b^{t} [-C(u_{1t}, u_{2t}, u_{3t}\,; Z) + \sum_{j\in A} b\, l^{j}_{t+1}(j_t + f^{j} - j_{t+1})\,] + \sum_{j\in D} b^{T} f^{j}\,(\bar{j} - j_T)\,,$$

where the set D is defined as $D=\{g, p\}$. The l^{j}_{t+1} (for $j \in A$) variable measures the change in the optimal value of the objective function with incremental changes in the state variables (plant quality attributes, preys, and predators) at time t. Similarly, the variable f^{j} (for $j \in D$) represents the change in the optimal value of the objective function with incremental changes in the respective terminal stock constraint.

Optimal Paths

In this section we focus on optimal paths of chemical and introduced predator controls.[9] The necessary condition for the chemical pest control variable, u_1, yields

$$(8)\qquad \left(b\, l^{a}_{t+1} f^{a}_{u_{1t}} + b\, l^{g}_{t+1} f^{g}_{u_{1t}}\right) \le C_{u_{1t}} - b\, l^{p}_{t+1} f^{p}_{u_{1t}}\,.$$

The planning rule in (8) indicates that the marginal benefits from chemical pest control must be equal to the marginal cost of chemical pest control, if pest controls are applied in time period t. When the marginal benefit is less than the marginal cost, then no chemical pest control will be applied in time period t. The marginal benefit consists of the benefit from increasing plant quality attributes $(b\, l^{a}_{t+1} f^{a}_{u_{1t}})$, and decreasing the insect populations $(b\, l^{g}_{t+1} f^{g}_{u_{1t}})$. The marginal cost of chemical pest control is equal to the immediate marginal cost $(C_{u_{1t}})$ plus the marginal cost of chemical pest control on introduced predators $(-b\, l^{p}_{t+1} f^{p}_{u_{1t}})$. This chemical control condition was previously discussed in Feder and Regev and in Marsh, Huffaker, and Long.

The necessary condition for introduced predators, u_2, yields

(9) $$\left(b\, l^{a}_{t+1} f^{a}_{u_{2t}} + b\, l^{g}_{t+1} f^{g}_{u_{2t}} + b\, l^{p}_{t+1} f^{p}_{u_{2t}}\right) \leq C_{u_{2t}}.$$

The planning rule in (9) indicates that the marginal benefits from introduced predators must be equal to the marginal cost of introduced predators, if introduced predators are applied in time period t. The marginal benefit consists of the benefit from increasing plant quality attributes ($b\, l^{a}_{t+1} f^{a}_{u_{2t}}$), decreasing the insect populations ($b\, l^{g}_{t+1} f^{g}_{u_{2t}}$), and increasing the predator population ($b\, l^{p}_{t+1} f^{p}_{u_{2t}}$). The marginal cost of introduced predators is equal to the immediate marginal cost ($C_{u_{2t}}$).

Conjunctively controlling insects with chemical or introduced predators initiates control trajectories not analyzed in Hueth and Regev, Feder and Regev, or Marsh, Huffaker, and Long. Optimal trajectories for chemical and biological control can be derived from the first order conditions of the bioeconomic model. There are four possible control trajectories from (8) and (9): simultaneous control, cyclical control, single control, and no control. All four possible cases are discussed below.

Case 1: Simultaneous control

Simultaneous control arises when u_{1t} and u_{2t} are greater than zero in the same time period. In this case, the joint use of chemical pesticides and introduced predators is optimal. Combining (8) and (9) results in a joint use equation:

$$(10)\ (b\, l^{a}_{t+1} f^{a}_{u_{1t}} + b\, l^{g}_{t+1} f^{g}_{u_{1t}})/(C_{u_{1t}} - b\, l^{p}_{t+1} f^{p}_{u_{1t}}) = (b\, l^{a}_{t+1} f^{a}_{u_{2t}} + b\, l^{g}_{t+1} f^{g}_{u_{2t}} + b\, l^{p}_{t+1} f^{p}_{u_{2t}})/(C_{u_{2t}})\ .$$

Equation (10) defines the necessary condition for control simultaneously with chemical pesticides and introduced predators. In effect, it is an equi-marginal principle, where inputs are used at the point where the ratios of marginal benefits to marginal costs are equal.

Case 2: Cyclical control

Cyclical control occurs when, for example, u_{1t}, u_{2s} and u_{1v} are greater than zero for $t<s<v$. In this case, the optimal pest management strategy is that of cycling between the use of introduced predators and chemical pesticides. This scenario would occur when equality holds in equation (8) in time period t and v, and in equation (9) in time period s, where $t<s<v$. Cycling may be necessary when the effectiveness of the control that is initially optimal decreases and then increases in effectiveness over the time periods that pest controls are needed. There may be biological reasons or government regulations that dictate cycling. Importantly, cycling may be appropriate in pest management settings where a grower is required to use nonconsecutive chemical controls to mitigate pest resistance.

Case 3: Single control

Single control occurs for chemicals when, for example, $u_{1t}>0$ in any time period and $u_{2t}=0$ in all periods. The necessary condition yields equality in equation (8) and an inequality in equation (9). Likewise, single control for introduced predators occurs when u_{2t}>0 in any time period and u_{1t}=0 in all periods. The necessary condition for introduced predators without chemical applications, u_2, yields equality in equation (9) and inequality in (8).

Case 4: No control

No control occurs when the marginal benefits are less than the marginal costs in both equations (8) and (9), which implies that u_{1t}=0 and u_{2t}=0 in all periods. In this case, the optimal pest management strategy is to use neither chemical pesticides nor introduced predators. Circumstances that would lead to this optimal solution include the condition where pest populations are low enough that they do not affect plant quality. On the other extreme, no control would be optimal when plant quality is below marketing standards and incurring additional pest management costs would be futile.

Terminal Conditions

The necessary conditions for the terminal period, T, identify additional circumstances under which the optimal trajectories of the model diverge from those of previous studies. Consider the terminal stock condition of the single pest g_T. The adjoint condition for the terminal value g_T is given by

(11) $$\frac{\partial B}{\partial Q}\frac{\partial Q}{\partial g_T}+\frac{\partial F}{\partial g_T}\leq l_T^g+f^g \quad .$$

This implies that, if the sum of the marginal changes in the visual aesthetic benefits plus expected future net benefits in period T with respect to g_T are less than the sum of the marginal changes in the optimal value of the objective function with respect to g_T from the pest co-state and co-constraint variables, then the terminal pest stock is zero (g_T =0). Otherwise, if the terminal stock is positive (g_T >0), then an equality exists in (11).

Focusing on the left hand side of (11), incrementing the terminal stock of pests decreases both the aesthetic benefits in period T at sales time and the expected net benefits for future time periods.

Next, consider the adjoint condition for the terminal value of the introduced predator, p_T,

$$(12) \qquad \frac{\partial B}{\partial Q}\frac{\partial Q}{\partial p_T} + \frac{\partial F}{\partial p_T} \leq l_T^p + f^p \ .$$

In (12), if terminal predator stock is positive ($p_T > 0$), then the marginal changes in the visual aesthetic benefits plus expected future net benefits in period T are just equal to the sum of the marginal changes in the optimal value of the objective function with respect to p_T from the predator co-state and co-constraint variables. If an inequality exists in (12), then terminal stocks are zero ($p_T = 0$).

Comparing the left hand side of (12) to that in (11) uncovers important intertemporal tradeoffs that balance marginal benefits of terminal stocks with expected net benefits of introduced predators in future time periods. Suppose $Q_{p_T} \leq 0$ in Equation (12). This suggests the conventional view that consumers often have a low tolerance level for any type of insect, including beneficial insects such as introduced predators.[10] Alternatively, educating consumers on the advantages of beneficial insects may alter negative perceptions, reducing the decrease in aesthetic benefits due to presence of beneficial insects. For instance, if consumers recognize and perceive that introduced pests are beneficial insects, $Q_{p_T} \geq 0$, which do not harm the plant or lead to future outbreaks of pests, then a higher tolerance level may be acceptable that rebalances chemical and introduced predator controls. Some consumers or retailers who understand the benefits of using biological control agents on ornamental crops may even be willing to pay a premium for a flower with beneficial insects.

Several circumstances merit further discussion. Consider the event when there is no carryover effect, or $F(g_T,p_T)=0$, which may occur if greenhouses are cleansed of insects between production periods or when pest and predators perish in the absence of plant habitat. In the left hand side of (11) and (12), there then is a decrease in marginal benefits that accrue from additional terminal stocks of predators or pests. Alternatively, in the event there is no visual aesthetic affect to fewer pests (e.g., pests are not visually detected), then $B_{g_T} = 0$ and $B_{p_T} = 0$. Here, incrementing terminal stocks of predators (pests) leads to a more traditional condition with an increase (decrease) in the expected future net benefits in period *T*. Finally, if growers are not constrained by terminal stocks of insects, then the co-constraint variables on the right hand side of (11) and (12) are trivial.

Economic-Aesthetic Thresholds

In all, equations (8)-(12) provide the necessary conditions from which to identify dynamically optimal economic thresholds (i.e., pest levels at which controls should be initiated). In fact, these can be reinterpreted as dynamically optimal aesthetic thresholds for ornamental crops, extending the previous concept of break-even aesthetic injury levels discussed in Higley and Pedigo.[11] For example, Sadof and Alexander, as well as Sadof and Raupp, calculate aesthetic injury levels for the twospotted spider mite on burning bush. Under this approach, adhoc measures of benefits and costs are equated to solve for the lowest pest density that will cause economic damage (i.e., the aesthetic injury level). This leads to a simple discrete planning rule: treat with recommended dosage level or else defer treatment. In contrast, the planning rules taken from the dynamically optimal aesthetic thresholds are marginal thresholds that vary over time, change across aesthetic ornamental attributes, and depend upon the set of economic and biological parameters that systematically structure the system. Although the economic-aesthetic thresholds are inherently more complicated to calculate than break-even aesthetic injury levels, we argue that they can still provide realistic planning rules in a theoretically consistent and more economically sensible manner.

Empirical Model

The floriculture bioeconomic model presented above is applied to the greenhouse production system of ivy geranium, which includes a single pest and predatory mite. Ivy geranium is an important bedding ornamental crop that was grown by over 1,700 producers in 36 states with a wholesale value of $28.7 million in 2001 (USDA). Ivy geranium are typically sold in 10 or 12-inch hanging-baskets. For the empirical model, we assume that the grower is producing ivy geranium in a 10-inch hanging basket, which is a common size for many GIV producers. The specific cultivar of ivy geranium used in the study is the "Amethyst 96." The pest is the twospotted spider mite, *Tetranychus urticae* Koch. The predatory mite is *Phytoseiulus persimilis* Athias-Henriot which is known to have potential for effective biological control of spider mites (Osborne, Ehler, and Nechols).

The grower is assumed to maximize the present value of current and future returns subject to population dynamics of TU and PP. The state variables of the system are the pest, g_t and the predator stocks, p_t. The control variables are the timing and rate of chemical controls, u_{1t}, and introduced PP, u_{2t}. The grower typically plans a water and nutritional regime in the beginning of the growing season that will produce a marketable quality plant. It is assumed that application rates of nitrogen (N) and phosphorous (P) are constant over the production period, which is a simplification of the conceptual model.[12] A specific application of the theoretical model to an ivy geranium grower can be specified as:

$$(13) \qquad \max_{u_{1t}, u_{2t}, u_{3t} \geq 0} \{ b^{T} P[(a_T(\boldsymbol{g}; N, P)] - \sum_{t=0}^{T-1} b^{t} [c_1 u_{1t} + c_2 u_{2t} + c_3]\}$$

subject to the insect prey, and predator net growth functions:

$$(14) \qquad g_{t+1} - g_t = g_t \left(1 - \frac{g_t}{g_m}\right) i_t^g - a\, g_t p_t - s\, u_{1t} g_t ,$$

$$(15) \qquad p_{t+1} - p_t = p_t \left(1 - \frac{p_t}{p_m}\right) i_t^p + w g_t p_t + u_{2t} ,$$

and terminal stock condition:

$$(16) \qquad g_T \leq \overline{g} .$$

The empirical model simplifies the grower's problem by incorporating only the essential requirements of the planner's problem including biological constraints and measures of plant growth and quality. The objective function, (13) is maximized subject to population changes of the pest, (14) and predator, (15), and terminal pest stocks, (16). Initial conditions and other parameters are described in table 1.

Data used to estimate empirical relationships were obtained from various greenhouse experiments as reported in Margolies et al. Data and methods are briefly discussed below for each empirical relationship. For further details see also Opit et al.; Opit, Margolies, and Nechols; and Schumacher.

Objective Function

The objective function in (13) represents the discounted returns over variable costs, which will be called profits in the remainder of the paper. The first term, $b^T P[a_T(\boldsymbol{g}; N, P)]$, is the growers discounted revenue, where $P[a_T(\boldsymbol{g}; N, P)]$ is composed of a price equation with price of the GIV as a function of quality. Plant quality, a_T, is an index that measures total plant quality, taking into account plant size, foliage color, plant shape, and number and size of flowers. Since ornamental crops are sold for their aesthetics, this index is established to capture not only plant growth, but also the visual appeal of the flower apart from insect presence. Plant quality is diminished by feeding of TU, which cause blistering and browning of the leaves and decrease overall plant growth. Plant quality at time T appears in the objective function, since it is the terminal condition of the plant that is relevant at sales time.

To establish a link between plant quality and a grower's decision with respect to pest and nutritional controls, the terminal value of plant quality is modeled as a quadratic function in N and P and linear in g_t:[13]

$$(17)\quad a_T = 5.4552 + 0.1386N + 2.0935P + 0.0298N * P - 0.0048N^2 - 0.5807P^2 - 0.0095\sum_{t=0}^{T-1} g_t,$$

(0.8367) (0.0616) (0.5755) (0.0262) (0.0016) (0.1835) (0.00348)

(R^2=0.33)

In (17) the terminal value of plant quality is a function of nutritional controls *N* and *P*, which are constant over the growing season, and the cumulative sum of the pest population over the growing season. [14] Sadof and Alexander and Boys and Burbutis have shown that cumulative mite density is significant in determining pest damage to plants.

In the objective function, price is modeled as an increasing function in plant quality, which is a deviation from previous pest management models and warrants further discussion. Ornamental crops are sold for their aesthetics; therefore we establish a price and plant quality relationship that takes into account that retailers and consumers alike pay more for higher quality ornamentals, ceteris paribus. To establish this price and quality relationship, expert growers in the floriculture industry provided discount rates for the various ranges of quality ratings assigned to the ivy geraniums in the greenhouse experiments previously discussed. The price for an ivy geranium with a quality rating of 9 to 10 is set at the average U.S. wholesale price as published by the USDA. Ivy geranium with ratings higher than or equal to 8 and below 9 are discounted 20% from the average U.S. wholesale price and ivy geranium with ratings higher than or equal to 7 and below 8 are discounted 50% from the average U.S. wholesale price. Flowers with ratings below 7 are determined to be unmarketable and are assigned a price of zero.

The empirical price relationship with lower and upper censoring is given by:

(18) $$E(P \mid L_1 < P < L_2) = b'x + s\left[\frac{f_1 - f_2}{\Phi_2 - \Phi_1}\right],$$

where L_1=lower limit, L_2=upper limit, $b'x = -16.6963 + 2.6767a_T$, $s = .6845$,

$\Phi_1 = [(L_1 - B'x)/s]$, $\Phi_2 = \Phi[(L_2 - B'x)/s]$, $f_1 = f[(L_1 - B'x)/s]$,

$f_2 = f[(L_2 - B'x)/s]$ (Maddala). The functions f and Φ are, respectively, the density function and the distribution function assuming a normal distribution. The standard errors for the slope and intercept term of $b'x$ are 0.7014 and 0.0912, respectively, and the resulting R^2 is 0.74. The price equation is estimated with 167 observations using a tobit model, with lower censoring at zero and upper censoring at the average U.S. wholesale price.

The second term in the objective function (13) represents the discounted variable costs over the growing season, where c_1 is the unit cost of applying chemical controls, c_2 is the unit cost of applying biological controls, and c_3 represents all other variable production costs including the cost of *N* and *P*. Per unit costs include purchased inputs and cost of application.

The terminal function, $F(g_T, p_T)$ is restricted to be zero since it is assumed there are no carryover benefits or costs associated with ending stocks of pests or predators in the next growing season. No carryover of benefits or costs is consistent with growers that manage their production by starting with pest-free cuttings and a clean greenhouse environment, which is a typical practice of many growers (Van Lenteren). Initially, we assume there is no visual aesthetic cost or benefit associated with the presence of pests. However, we later relax this assumption and consider several scenarios to determine the influence of insect presence on ornamentals and the resulting impact on optimal decision rules.

Pest-Predator Models

The TU and PP population models are represented by equations (14) and (15), respectively. The left-hand sides of the equations are the weekly change in their respective populations. The first terms on the right-hand sides of equations (14) and (15) are logistic growth functions of the TU and PP, respectively. The remaining right hand side terms are interactions between TU and PP and chemical controls.

Intrinsic growth rates and environmental carrying capacities play key roles in identifying the predator-pest growth functions and their response to nutritional inputs. The variable i_t^g in equation (14) is the intrinsic growth rate of TU that depends on the nutritional inputs. The intrinsic growth rate is a linear function of nitrogen and phosphorous and is consistent with prior research (Wermelinger, Oertli and Baumgartner). This equation links growers' nutritional decisions to their pest management decisions. The intrinsic growth rate of PP is represented by the parameter i^g_t. The parameters, g_m and p_m are the TU and PP's environmental carrying capacity, respectively.

The remaining terms on the right-hand side identify interactions between chemical and predator controls and pest stocks. The term, $a g_t p_t$ in equation (14) measures the decline in the TU due to the predator p_t, where a is a predation constant. The term, $s u_{1t} g_t$ in equation (14) measures the decline in the TU population due to application of chemical controls, where s is a constant. The term $w g_t p_t$, in equation (15) measures the increase in the PP population due to the pest TU, where w is a constant. Based on prior research using combined chemical and predator controls, it is assumed that selective application of pesticide is compatible with use of predatory mites (Trumble and Morse). The last term in equation (15), u_{2t}, is the introduction of predators, which increases the PP population.

The empirical relationships of (14) and (15) are estimated as

$$19)\ g_{t+1}-g_t = g_t\left(1-\frac{g_t}{12}\right)(0.012992P + 0.187432N - 0.00793(P*N)) - 0.032714 g_t p_t - u_{1t} g_t$$

(0.0052) (0.0654) (0.0049) (0.0142)

(R^2=.31)

and

$$(20)\ p_{t+1} - p_t = p_t\left(1-\frac{p_t}{2}\right)0.067919 + 0.011188 g_t p_t + u_{2t},$$

(0.0120) (0.0182)

(R^2=.63)

where all variables are as previously specified and numbers in parenthesis directly underneath the equations are standard errors. The net growth functions are estimated (using 234 observations) in SAS using a nonlinear ITSUR estimator.

Although the terminal pest stock is bounded in (16), in the scenarios presented below we relax this assumption and consider both the terminal condition and a free terminal stock. The predator stock condition is not restricted in all formulations, since if the TU is restricted to be zero the PP disperses due to lack of a food source. This provides two extreme cases with which to compare optimal decision rules due to variation in terminal stock constraints.

Analysis and Results

Scenarios of the empirical model are calculated to determine the effects of variation in initial stocks, terminal stock constraints, the input price ratio (the price of introduced predators /price of chemical control), and the damage index on profit and control trajectories. Following Standiford and Howitt, the model is solved as a nonlinear programming problem using GAMS software and the solver, minos5 (Brooke, Kendrick, and Meeraus). A range of input levels of both N and P are varied in all scenarios, rather than explicitly specifying N and P as control variables. Nine levels of input rates are used for N (10, 11, 12, 13, 14, 15, 16, 17, and 18millimolar (mM)), and four input rates are used for P (0.55, 1.10, 1.65, and 1.77mM). Nitrogen and P levels are constrained to be less than 18.00mM and 1.77mM, respectively, since the plant quality equation (17) is fairly flat over a range of nutritional levels that will produce GIV of similar physical quality. Each scenario reported in table 2 is optimized over the 36 possible combinations of nine levels of N and four levels of P to determine the optimal decision rules.

Calibration Scenarios

Four scenarios restricting the damage parameter (the last parameter in equation 17) to zero in the plant quality function are generated to test the dynamics of the TU and PP without chemical or introduced biological controls. These results provide comparison to other scenarios and verification of biological dynamics independent of human influence. It also provides starting values for scenarios involving chemical and biological controls using the nonlinear solver in GAMS. Two calibration scenarios are run with initial TU of 10.0 and 3.0 and no initial PP. Two additional calibration scenarios are run with initial TU of 10.0 and 3.0 and initial predators of 2.0 and 1.0, respectively. All four baseline scenarios result in the same optimal levels of N and P of 18.0mM and 1.77mM, respectively, and no pest controls are selected. The resulting plant quality index of 9.24 is identical across all four scenarios. The population dynamics of the TU and PP are found to be consistent with greenhouse experiments reported by Margolies et al. and Opit, Margolies, and Nechols.

Chemical and Biological Control Scenarios

Assuming a nonzero damage parameter in the model, high initial infestation of TU of 10.0 and an upper bound on the chemical kill rate of 90.0%, seven different scenarios are formulated in the upper half of table 2. Scenario 1 is the base case with each of the six remaining scenarios defined by varying one of the following parameters: the initial stock of predators, the terminal pest constraint, the input price ratio, the upper bound chemical kill rate, the predation parameter, a, and the effect of TU on plant quality (the last parameter in equation 17). Since applying chemical pesticides to control for the twospotted spider mite on GIV does not typically eradicate the pest, we establish a ceiling on the percentage of mites that can be harvested with chemical pesticides. For this study we select an upper bound kill rate of 90%, which is reasonable based on prior research on chemical efficacy trials (O.F.A. Services Inc.).

Results of the seven scenarios are provided in the lower half of table 2. Initial stocks of predators are zero with the exception of Scenario 4. All seven formulations (with initial TU of 10) result in chemical pesticides as an optimal control in the initial period, with kill rates ranging from 60.0% to 90.0%. The optimal inputs of N and P are identical across all seven scenarios with N at 18mM and P at 1.77mM. The seven scenarios resulted in profits ranging from $3.35 to $3.69 per plant, and plant quality indexes ranging from 9.04 to 9.15.

In Scenario 1, the baseline input price ratio of cost of introduced predators/cost of chemical control is 1.1875. The optimal control is the application of chemical controls with a kill rate of 0.90 in periods 1, 2, 3, and 4. The quality index is 9.11, and the price of the ivy geranium is $7.69 with a resulting profit of $3.61/hanging basket. Scenario 1 is used as a comparison to scenarios 2 through 7, wherein a single parameter is altered in scenarios 2 through 7 that differs from Scenario 1.

When the input price ratio is reduced to 0.7917, which is an increase in the cost of chemical control by 50% (Scenario 2), introduction of predators becomes optimal. The simultaneous combination of 4.65 introduced predators and chemical application with a kill rate of 0.90 in the initial period is the optimal solution. This scenario results in less frequent chemical applications and a higher quality index and price than Scenario 1. However, the resulting profits of $3.58 are lower than Scenario 1 by $.03.

When the upper bound of chemical kill rate is lowered to 0.60 (Scenario 3), it becomes optimal to introduce 1.12 predators in period 1 along with applying chemical control with a kill rate of 0.60 in periods 1, 2, 3, 4, 5, 6, and 7. This scenario results in a quality rating, price and profit of 9.04, $7.50 and $3.35, respectively. The rating, price, and profit in Scenario 3 are lower than Scenario 1, which is as expected with a more restrictive upper bound on the chemical kill rate.

Increasing the initial stock of predators from 0 to 2 (Scenario 4) results in applying 2.65 predators and chemical control with a kill rate of 0.90 in period 1. This scenario results in only one chemical control application, in contrast to Scenario 1, which results in four chemical control applications. This suggests that a grower can take advantage of initial predators in controlling pests and reduce the number of applications of chemical pesticides. The resulting quality rating, price and profits are 9.15, $7.79, and $3.69, respectively, all of which exceed those in Scenario 1.

Restricting the terminal stock of pests to zero (Scenario 5) with initial predator set to zero, results in applying 4.65 predators in period 1 and applying chemical control in period 1 with a kill rate of 0.90. The results from Scenario 5 are similar to Scenario 4 in that it results in fewer applications of chemical controls than Scenario 1. In circumstances where there is no tolerance for pests when marketing flowers, the use of introduced predators in conjunction with chemical control is optimal. Scenario 5 results in a higher quality index and price but a lower (albeit nearly identical) profit relative to Scenario 1. A lower profit is expected, since the model is more limiting when a terminal stock restriction is added.

When reducing the effectiveness of a predator by adjusting the predation parameter a , from 0.0327 to 0.0185 (Scenario 6) the optimal solution to the planners problem is identical to Scenario 1. Since introduced predators are not optimal in Scenario 1, reducing the predation parameter does not affect the optimal solution. The quality index, price and profits are identical to Scenario 1.

Decreasing the parameter that measures the effect of the pest population on plant quality from –0.009 to –0.012 (Scenario 7) results in the same pest management decision rule as Scenario 5. The combination of introduced predators of 4.65 and the application of chemical control with a kill rate of 0.90 in period 1 is optimal. Similar to Scenario 5, the increase in the negative effect of the pest population on plant quality by 1/3 reduces the number of chemical application rates from four as in Scenario 1 to only one. Scenario 7 results in a higher quality index and price but lower profit than Scenario 1. The lower profits are expected since the pests have a larger negative effect on plant quality and price.

Further Scenarios

In addition to the scenarios with high initial stocks, seven additional scenarios (not reported in table 2) are formulated with a lower initial stock of three pests per young leaf. With a lower initial stock of pests, the scenario restricting the terminal stock of pests to zero results in simultaneous control of applying both introduced predators and chemical pesticides in the initial period as the optimal decision rule. The other six scenarios with a lower initial stock of pests result in singular control with the application of chemical controls as the optimal solution in the first period.

Finally, presuming predators are visibly detected, we investigate potential effects of the presence of predators on ivy geranium at sales time of the plant. That is, we compare the conventional view that any insects on ornamentals have negative impacts on benefits relative to the less conventional or organic view that they have positive impacts on benefits. Suppose the existence of predators in the terminal time period is negatively perceived by the consumer and the price of ivy geranium is discounted by 10%. With this price discount, all scenarios reported in table 2 would result in single control with chemical pesticides, with scenarios 2, 4 and 7 resulting in more frequent application of chemical pesticides as compared to the frequency of applications reported in table 2. In contrast, suppose the presence of predators in the terminal time period is perceived as a positive benefit by the consumer and a 10% premium is added to the price of ivy geranium. With the inclusion of the price premium, the optimal pest management strategy does not change for scenarios 2, 3, 4, 5, and 7. However, in scenarios 1 and 6, the optimal pest management strategy is simultaneous control with predators and chemical pesticides, rather than single control with chemical pesticides. In addition, Scenario 1 results in less recurrent application of chemical pesticides compared to the occurrence of applications reported in table 2. In all, these simulated results provide supporting evidence that educating consumers on the advantages of beneficial insects may reduce the frequency of chemical pesticide applications by greenhouse floriculture producers.

Discussion

In the various scenarios reported above we conduct sensitivity analysis to evaluate the effects of changes in parameters or assumptions in the model on the optimal rates of cultural and pest controls. The model is robust in that all scenarios result in optimal rates of N at 18mM and P at 1.77mM. These optimal rates of N and P apply to the cultivar "Amethyst 96", which is used in this study. The overall dominating strategy with high initial infestation is to initially introduce predators and apply chemical pesticides, which is consistent with simultaneous control (Case 1) in the theoretical section of the paper. Here, the efficient input allocation is where the ratios of marginal benefits and costs for biological and chemical controls are just equal. This strategy is optimal in five out of the seven scenarios (2, 3, 4, 5, and 7) with high initial infestation of pests, including the scenario of zero pest tolerance. The information needed by growers to implement this strategy is compatible with an integrated pest management program that includes frequent monitoring of pest density.

Across all seven scenarios, the aesthetic threshold in the initial period is 10 mites per leaf. After the initial period, the pest threshold decreases over the growing season from period 1 thru period 7, and then increases slightly from period 7 thru period 10. This demonstrates that after the initial period growers of GIV have a lower threshold for pests in the early periods of production and a higher threshold for pests in later periods of production. This finding is consistent with a common pest management strategy of greenhouse growers who use preventive application of pesticides or biological controls early in the growing season and less frequent applications in the later periods of production.

A key economic measure of interest to growers is the profitability of the optimal decision rules. The profitability across all scenarios ranges from $3.35 to $3.69/hanging basket. This range of profit demonstrates that pest management decisions can have a large impact on a grower's profitability. When comparing profits across scenarios, Scenario 4, where an initial stock of predators exist, results in the highest profits. In addition, Scenario 4 results in the highest quality rating, which is consistent with conversation with growers who indicate that growing the highest quality plant possible is the most profitable. A vital implication of this empirical finding is that when a predator population is naturally colonized, the grower can augment the natural population with introduced predators to optimize profits and simultaneously harvest fewer pests with chemicals. Contradictory to most current pest control practices used by many growers, these results demonstrate that the use of biological control methods can be optimal for a profit-maximizing grower.

An additional important contribution of this research is the potential to reduce pesticide use through educating consumers on the benefits of natural predators. As presented in the theoretical model, consumers typically have a low tolerance for any type of insect, including beneficial insects. Incorporating this consumer characteristic into the empirical model, by discounting the market price of ivy geranium (due to visibly detected predators), results in more frequent application of chemical pesticides. However, adding a premium to the price of ivy geranium, due to the existence of beneficial insects, results in less frequent application of chemical pesticides. This analysis suggests that educating consumers on the benefits of predators on ornamental crops could result in fewer applications of pesticides and an increase in the use of predators by greenhouse floriculture producers. With the growing interest in reducing pesticide use, this information can be used to make policy decisions targeted toward increasing the use of biological control methods by providing economic incentives to educate consumers on the benefits of predatory insects.

These results also have implications from a social perspective. That is, scheduled or prophylactic chemical applications are not always necessary in greenhouse production. Instead, growers can maximize profits by harvesting fewer pests with chemical applications and more pests with introduced predators. Furthermore, conjunctive use of chemicals and introduced predators that results in less intensive chemical use may be an alternative to cycling chemicals to combat pest resistance. These are a win-win situation since a grower can maximize profits and reduce the use of chemical pesticide applications, which may have negative externalities associated with human health and the environment.

Conclusion

The motivation for this interdisciplinary research is interest in developing alternative pest management strategies to prophylactic pesticide applications in ornamental crop production. A conceptual bioeconomic model of floriculture production with aesthetic benefits is developed to determine optimal decision rules and economic thresholds within a dynamic framework. A grower has the option of single, simultaneous, cyclical or no control using chemical pesticides and/or introduced predators to control for pests. The analysis highlights the relative effectiveness of chemical pesticides and biological controls and their respective costs/benefits in any one time period as determinants of whether optimal pest management decision rules are singular, cyclical or simultaneous in nature. The conceptual model is general enough in nature that it can be applied to production systems other than ivy geranium.

In addition, the expected future net benefits of the predator at the terminal period, which is typically viewed as negative, may have an impact on whether the optimal decision rule results in single or simultaneous control using chemical pesticides and/or biological controls. As is demonstrated in the empirical model, there is potential to reduce the frequency of pesticide applications in greenhouse floriculture production by educating consumers on the benefits of predatory insects. Due to the interest in reducing pesticide use in greenhouse floriculture production, the results from this research are relevant in policy decisions targeted toward achieving this objective through education. The policy implications from this study will be even more pertinent in the future due to further development of pest resistance or additional governmental regulations extending pesticide restrictions.

A specific empirical application of the model, which consists of a greenhouse-grown ivy geranium, one of its major pests, *Tetranychus urticae* Koch, and a predatory mite, *Phytoseiulus persimilis,* is presented along with analysis of results. Interestingly, there are circumstances when the combination of introduced predators and chemical control results in the highest profits. When growers are faced with a marketing constraint such that terminal stocks of pest are restricted to be zero or there is an initial population of predators, the combination of introduced predators and chemical control is the optimal decision rule. These results demonstrate that growers can optimize their profits by taking advantage of introduced predators and reduce the frequency or rates of chemical applications. In addition, the results from this model are robust in that optimal rates of cultural controls are the same across all scenarios, and the dominating strategy for pest management is the simultaneous use of chemical and introduced biological controls.

Furthermore, this research provides a foundation for better understanding the economic incentives behind using both chemical pesticides and biological controls either simultaneously or cyclically to manage plant quality and pests in greenhouse floriculture production.

Finally, this research does not quantify the social benefits of the potential reduction of chemical pesticide applications by greenhouse growers. The results of this research demonstrate that further economic research on the social value of reducing pesticide applications is needed. The potential social benefits may warrant policy that provides economic incentives to growers to increase the use of biological controls in the future.

Appendix A: First-Order Conditions

To maximize the objective function in (1), equations (2)-(6) must be satisfied in addition to the following:

maximum conditions:

$$\frac{\partial L}{\partial u_{kt}} = -b^{t} C_{u_{kt}} + b^{t+1} \sum_{j \in A} b \, l^{j}_{t+1} f^{j}_{u_{kt}} \le 0, \quad \frac{\partial L}{\partial u_{kt}} u_{kt} = 0, \quad u_{kt} \ge 0$$

for controls k=1,2,3

adjoint conditions:

$$b \, l^{a}_{t+1} - l^{a}_{t} = -b \sum_{j \in A} l^{j}_{t+1} f^{j}_{a_t}$$

for state variables $k = a_t, g_t, p_t$ for $t = 1, \ldots, T-1$

Kuhn- Tucker/boundary conditions:

$$l^{a}_{T} = \frac{\partial B}{\partial a_T}$$

$$\frac{\partial B}{\partial g_T} + \frac{\partial F}{\partial g_T} \le l^{g}_{T} + f^{g}, \quad \frac{\partial L}{\partial g_T} g_T = 0$$

$$\frac{\partial B}{\partial p_T} + \frac{\partial F}{\partial p_T} \le l^{p}_{T} + f^{p}, \quad \frac{\partial L}{\partial p_T} p_T = 0$$

References

Bonhoeffer, S., M. Lipsitch, and B. Levin. "Evaluating Treatment Protocols to Prevent Antibiotic Resistance." Proceedings of the National Academy of Sciences of the United States October 29, 1997: 94(22):12106-12111.

Boys, F., and P. Burbutis. "Influence of Phytoseiulus Persimilis on Populations of Tetranychus Turkestani and the Economic Threshold on Roses." *Journal of Economic Entomology* 65(1972):114-117.

Brooke, A., D. Kendrick, A. Meeraus. *GAMS: A User's Guide*. Redwood City, CA: The Scientific Press, 1988.

Davis, R. and C. A. Tisdell. "Alternative Specifications and Extensions of the Economic Threshold Concept and the Control of Livestock Pests," in *Economics of Pesticides, Sustainable Food Production, and Organic Food Markets* (eds. D. C. Ha.. and L. J. Moffitt), JAI, New York, 2002.

Environmental Protection Agency. Pesticide Registration (PR) Notice 2001-5, http://www.epa.gov/opppmsd1/PR_Notices/pr2001-5.pdf, October 4, 2002.

Feder G. and U. Regev. "Biological Interactions and Environmental Effects in the Economics of Pest Control." *Journal of Environmental Economics and Management* 2(December 1975):75-91.

Feichtinger, G., A. Novak, and F. Wirl. "Limit Cycles in Intertemporal Adjustment Models: Theory and Application." *Journal of Economic Dynamics and Control* 18(March 1994):353-380.

Hall D. and R. Norgaard. "On the Timing and Application of Pesticides." *American Journal of Agricultural Economics* 55(1973):198-201.

Higley, L. G. and L. P. Pedigo. *Economic Thresholds for Integrated Pest Management*, University of Nebraska Press, Lincoln, NE, 1996.

Hoddle M. and R. Van Driesche, and J. Sanderson. "Biological Control of Bermisia argentifolii on Poinsettia with Inundative Releases of Encarsia Formosa: Are Higher Release Rates Necessarily Better?" *Biological Control* 10(1997):166-179.

Hueth, D. and U. Regev. "Optimal Agricultural Pest Management with Increasing Pest Resistance." *American Journal of Agricultural Economics* (August 1974):543-552.

Jonas, V. "Optimizing Fertilization and Watering Regimes of Ivy Geraniums." Masters Thesis, Kansas State University, 2000.

Laxminarayan, R. "Bacterial Resistance and the Optimal Use of Antibiotics." Resources for the Future, Discussion Paper 00-36, September 2000.

Laxminarayan, R. and G. Brown. "Economics of Antibiotic Resistance: A Theory of Optimal Use." Journal of Environmental Economics and Management 42(September 2001):183-206.

Maddala, G.S., *Limited Dependent and Qualitative variables in Econometrics*. Cambridge UK: Cambridge University Press, 1983.

Margolies, D.D., J.R. Nechols, K.A. Williams, T. Kastens, and T.L. Marsh. "Integrated Crop Management: Spider Mites on Greenhouse-grown Ivy Geraniums." Final Report North Central IPM Grants Program, Grant No. 58-5430-8-131, CREES Agreement No. 99-34103-7657 2002.

Marsh, T. L., R. G., Huffaker, and G. E. Long. "Optimal Control of Control of Vector-Virus-Plant Interactions: The Case of Potato Leafroll Virus Net Necrosis." *American Journal of Agricultural Economics* 83(August 2000):556-569.

Moffit, L. J. "Incorporating Environmental Considerations in Pest Control Advice for Farmers," *American Journal of Agricultural Economics* 70(August 1988):628-634.

Ohio Florists' Association (O.F.A.) Services Inc. "Tips on Selecting Pest Management Strategies." June 2001.

Onofrey, D. "We've Got the Power." *Greenhouse Grower* (October 1998): 1-16.

Opit, G., D. C. Margolies, and J. R. Nechols. "Within-Plant Distribution of Two-spotted Spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), on Ivy Geranium: Development of a Presence-Absence Sampling Plan." In Press *Journal of Economic Entomology*, 2002.

Opit, G., V. M. Jonas, K.A. Williams, D. C. Margolies, and J. R. Nechols. "Effects of cultivar and Irrigation Management on Population Growth of the Twospotted Spider Mite *Tetranychus urticae* on Greenhouse Ivy Geranium." In Press *Experimental and Applied Acarology*, 2002.

Osborne, L.S., L.E. Ehler, & J.R. Nechols. "Biological Control of the Twospotted Spider Mite in Greenhouses." Florida Agricultural Experiment Stations, Institute of Food and Agricultural Sciences, Tech. Bulletin 853. 1985 40 pp.

Sadof C. and C. Alexander. "Limitations of Cost-benefit Based Aesthetic Injury Levels for Managing Twospotted Spider Mites (Acari: Tetranychidae)." *Journal of Economic Entomology* 86(October 1993):1516-1521.

Sadof, C. and M. Raupp. "Aesthetic Thresholds and Their Development," *Economic Thresholds for Integrated Pest Management*, edited by L. Higley and L. Pedigo. Nebraska: University of Nebraska Press, 1996.

Schumacher, S. "Economic Analysis of Production and Pest Management Decisions Confronting Greenhouse Growers." PhD Dissertation, Kansas State University, 2002.

SePRO. *Akari Fact Sheet*. July 18, 2002. Available at: http://www.sepro.com/horticulture/akari/akair_fact_sheet.htm.

Standiford, R.B. and R.E. Howitt. "Solving Empirical Bioeconomic Models: A Rangeland Management Application," *Amer. J. Agr. Econ*. 74(May 1992):421-433.

Trumble, J. and J. Morse. "Economics of Integrating the Predaceous Mite Phytoseiulus persimilis with Pesticides in Strawberries." *Journal of Economic Entomology* 86(June 1993):879-885.

Uniroyal Chemical. *Floramite Product Use Guide*. July 18, 2002. Available at: http://www1.infolinksa.com/skwitco/tablesubs/floramite.asp.

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service. *Floriculture Crops 2001 Summary*. April 2002.

Van Lenteren, J.C., "A Greenhouse Without Pesticides: Fact or Fantasy?" *Crop Protection* 19(2000):375-384.

Wermelinger, B., J. Oertli, and J. Baumgartner. "Environmental Factors Affecting the Life-Tables of *Tetranychus urticae* (Acari: Tetranychidae)." *Experimental and Applied Acarology* 12(1991):259-274.

Wirl, F. "The Cyclical Exploitation of Renewable Resource Stocks May be Optimal." *Journal of Environmental Economics and Management* 29(September 1995):252-261.

Zhang, Z. and J. Sanderson. "Twospotted Spider Mite and Phytoseiulus persimilis on Greenhouse Roses: Spatial Distribution and Predator Efficacy." *Horticultural Entomology* 88(April 1995):352-357.

Table 1. Parameter Values for Empirical Model

Parameter	Description	Units	Value
T	time period	Week	1
c_1	chemical cost per application	$/hanging basket	.0400 [a]
c_2	cost of biological controls	$/predator	.0475[b]
c_3	other production costs	$/hanging basket	3.93[c]
g_0	TU initial condition	TU/ young leaf/t	3.0 and 10.0
g_m	TU carrying capacity	TU/young leaf	12.0[d]
i^g_t	TU intrinsic growth rate	t^{-1}	.03188[d]
a	predation parameter	(predators/plant)	.0327[d]
s	kill parameter	(predators/plant)	1.0[d]
p_0	PP initial condition	PP/plant/t	0.0
p_m	PP carrying capacity	PP/plant	2.0[d]
i^p_t	PP intrinsic growth rate	t^{-1}	.0679[d]
w	PP growth parameter	t^{-1}	.0112[d]

[a]The chemical cost per plant per application is from personal communication with ivy geranium growers in the floriculture industry. [b]The predatory cost per plant is from personal communication with representatives in the biological control industry. [c]Costs are obtained from personal communication with ivy geranium growers. [d]Biological parameters are based on findings from greenhouse experiments conducted at Kansas State University (Schumacher).

Table 2. Chemical and Biological Scenario Assumptions and Results (with initial TU of 10).

Scenario	1 Baseline	2	3	4	5	6	7
			Assumptions[a]				
Initial Stock of PP	0	0	0	**2**	0	0	0
Terminal Stock Restriction	free	free	free	free	**0**	free	free
Upper bounds on chemical kill rate	0.90	0.90	**0.60**	0.90	0.90	0.90	0.90
a [b]	0.0327	0.0327	0.0327	0.0327	0.0327	**0.0185**	0.0327
Pest effect on plant quality	-0.009	-0.009	-0.009	-0.009	-0.009	-0.009	**-0.012**
Price Ratio[c]	1.1875	**.7917**	1.1875	1.1875	1.1875	1.1875	1.1875
			Results				
Profit($/GIV)	3.61	3.58	3.35	3.69	3.60	3.61	3.52
Quality Index	9.11	9.15	9.04	9.15	9.15	9.11	9.12
Price of Ivy Geranium($/GIV)	7.69	7.79	7.50	7.79	7.79	7.69	7.71
Timing of Chemical[d]	1,2,3,4	1	1,2,3,4, 5,6,7	1	1	1,2,3,4	1
Chemical Kill Rates[e]	0.90	0.90	0.60	0.90	0.90	0.90	0.90
Timing of Introduced PP[c]	-	1	1	1	1	-	1
Introduced PP[f]	-	4.65	1.12	2.65	4.65	-	4.65

[a]Bolded parameter represents change from Scenario 1, which is the baseline.
[b]Predation parameter in the PP net growth function.
[c]The price ratio is the price of introduced predators/price of chemical control
[d]The beginning of the week in the production schedule.
[e]The percentage of pests killed when chemical pesticides are applied.
[f]The number of predators introduced per GIV.

Endnotes

[1] Van Lenteren (2000) provides an excellent review article motivating and historically documenting the increasing use of integrated pest management programs that limit conventional pesticides in greenhouses throughout the world. For further information, see the September 1989 issue of the *Florida Entomologist*, which devoted a symposium to integrated pest management programs for ornamental crops.

[2]Personal communication with greenhouse growers indicates that visual presence of insects on ornamentals is often not desirable to consumers. See also discussions in Higley and Pedigo.

[3] See http://www.epa.gov/ for discussion of pesticide regulations and Onofrey for discussion of industry concerns.

[4] Sadof and Raupp discuss the concept of aesthetic threshold levels from an entomological perspective. Davis and Tisdell (2002) provide an overview of alternative economic thresholds, but do no address aesthetic threshold levels.

[5] This is a deviation from Hueth and Regev's pest management model, where it is assumed that a nonpest control input has no effect on the pest population.

[6] See Hueth and Regev or Marsh, Huffaker, and Long for further insight.

[7] Even if positive terminal stocks of insects are acceptable, their presence may decrease aesthetic benefits to the consumer. This is reflected in a benefit function that is nonincreasing in pest and introduced predator stocks.

[8] See Uniroyal Chemical and SePRO.

[9] This is because of the novel interactions between chemical and introduced predators and because these control variables turn out to be the interesting variables in the empirical model discussed ahead. Further, Hueth and Regev previously addressed necessary conditions for cultural controls. The full set of optimal decision rules is provided in the appendix.

[10] Sadof and Raupp suggest that insect presence on ornamental plants is perceived as an indication of lower quality because consumers anticipate future pest outbreaks or aesthetic damage.

[11] Moffit provides a good overview of break-even relative to marginal pest thresholds.

[12] Although this simplifies the empirical model, the results still provide practical decision rules for greenhouse growers and allow the focus to be on the pest and introduced predator interactions.

[13] A quadratic response to N and P is specified, which is consistent with prior research (Jonas). One hundred and sixty seven ivy geraniums were grown in a greenhouse with varying rates of N, P and mite density (Margolies et al). At the end of production, each plant was assigned a plant rating using a scale of 1 to 10, with 10 being the highest quality. The plant quality ratings are assigned taking into consideration volume, shape, foliage color, and number and size of inflorescences. Plant quality ratings of 7 to 10 are considered to be of commercial quality and are marketable.

[14] Typically dry weight is used as a measure of plant growth, but this method does not take into account the appearance of the ornamental crop, which is very important when marketing. The plant quality ratings are found to be highly correlated (rho=0.80) with dry weight. This indicates that the plant quality index is a good proxy for plant growth that also takes into consideration the plant size, shape, foliage color and the number and size of flowers (Schumacher).