# Optimal Pest Control in Greenhouse Production of Ornamental Crops

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**Abstract**

We develop a conceptual bioeconomic model of pest control for floriculture production in greenhouses growing crops with aesthetic benefits. In the greenhouse production environment, cultural controls (e.g., fertilization and irrigation regimes) and pest controls (chemical or biological) are applied at frequent time intervals. Necessary conditions of the model identify trajectories (e.g., simultaneous, single, or cycling controls) that define decision rules and economic thresholds for profit maximizing growers. The necessary conditions also highlight intertemporal tradeoffs between aesthetic benefits (plant quality and visual presence of arthropods) and expected future net benefits of arthropod stocks, which have important policy implications. The floriculture bioeconomic model is applied to the greenhouse production system of ivy geranium, which includes a single arthropod pest and predatory mite. Results demonstrate that growers can optimize profits, while still retaining acceptable aesthetic attributes, and reduce frequency of chemical applications by taking advantage of introduced predators released to control pests.

JEL Classification: Q20, Q57

<u>Key words</u>: aesthetic benefits, bioeconomic model, biological control, dynamic optimization, economic threshold, floriculture

## 1. Introduction

Pest control is vital to growers of ornamental greenhouse crops, which are subject to physical damage by arthropods (insects and mites) that reduces the crop's aesthetic value. Pest control in greenhouse crops is unique and different relative to most pest control in traditional agricultural field crops. Increasingly, greenhouse growers are striving to optimally balance the application of chemical and introduced biological 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, cultural controls (e.g., fertilization and irrigation regimes) and pest controls (chemical or biological) are applied at frequent time intervals.[2] In this process, growers make important intertemporal tradeoffs among cultural and pest controls to keep both plant quality and visual levels of arthropods (pest or predators) at acceptable levels.[3] Our intention is to extend traditional pest control models (Feder and Regev, 1975; Hall and Norgaard, 1973; Hueth and Regev, 1974) 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 (2002) through the

[1] Based on a survey of floriculture producers across the U.S. approximately 50% of the growers surveyed currently use or have used biological controls in their floriculture production system (Schumacher, 2002).
[2] 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.
[3] 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 (1996).

Food Quality Protection Act and by the dynamic nature of arthropod and plant stocks.[4] 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 cultural inputs, introduced biologicals, and chemicals to control stocks of pest that damage ornamentals. With dynamic arthropod and plant stocks, timing of pest controls plays a critical role in greenhouse pest management practices constrained by pesticide regulations. For example, producers must often avoid consecutive applications of the chemicals to mitigate pest resistance (Environmental Protection Agency, 2002). Moreover, when timing the release of predators to control plant-damaging pests during a production cycle, 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 arthropods on plants at sales time. These and other issues provide the economic motivation to understand the dynamically optimal combination of chemicals, introduced predators, and cultural controls in producing ornamentals for their aesthetic benefits.

Previous pest control models include Hueth and Regev (1974), 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 (1975) examined insect-natural predator interactions and environmental effects in pest control. Marsh et al. (2000) investigated vector-virus-plant interactions in potato production. Other optimal control models have investigated the use of simultaneous or cyclical control strategies to

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[4] See http://www.epa.gov/ for discussion of pesticide regulations and Onofrey (1998) for discussion of industry concerns.

address antibiotic resistance (Bonhoeffer et al., 1997; Laxminarayan, 2000; Laxminarayan and Brown, 2001) and optimal harvesting of renewable resources (Feichtinger et al., 1994; Wirl, 1995). 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 greenhouse environment, nor do they investigate the tradeoffs between chemical and introduced biological controls in establishing aesthetic threshold levels in a theoretically consistent economic framework.[5] The greenhouse environment allows use of controls generally not feasible in traditional agricultural production. For example, watering frequency and fertilizer rates are micro-managed and can be used to influence interactions among plants and arthropods. Further, given restrictions on pesticide use in greenhouses, introduced predators are commonly used to control greenhouse pests (Hoddle et al., 1997; Van Lenteren, 2000; Zhang and Sanderson, 1995). It is anticipated that introduced predators can be used to conjunctively control the visual presence of pests on plants and plant quality by preying on arthropod-pests.

The purpose of the current study is two-fold. The first objective is to develop a conceptual bioeconomic model for the greenhouse floriculture industry that will lead to optimal decision rules and economic thresholds within a discrete time framework. Necessary conditions of the model identify trajectories (e.g., simultaneous, single, or cycling controls) that define decision or planning rules and economic thresholds for profit maximizing growers producing crops with aesthetic attributes. The necessary conditions

[5] Sadof and Raupp (1996) 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.

also highlight intertemporal tradeoffs between aesthetic benefits and expected future net benefits of arthropod 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 (EPA, 2002).

The second objective is to present an exploratory empirical application of the bioeconomic model, which consists of greenhouse-grown ivy geranium, <u>Pelargonium peltatum</u> (L.)'Her ex Ait (GIV), one of its major (arthropod) pests, <u>Tetranychus urticae</u> Koch (TU), and a predatory mite, <u>Athias-Henriot</u> (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, this methodology is applicable to other crops that produce output with aesthetic benefits and are hindered by pest control problems.

## 2. 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, 1996). The state variables of the system are physical plant quality (distinct from quality influences induced by the visual presence of arthropods), $a_t$, pest stocks, $g_t$, and prey-specific predator stocks, $p_t$, per unit area at time $t$. The control variables are timing and rate of chemical pest controls, $u_{1t}$, introduced biological controls, $u_{2t}$, and cultural 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 arthropods. 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 $\beta = (1+\delta)^{-1}$ with discount rate $\delta$.

The greenhouse grower's optimization problem is

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

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

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

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

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

initial stocks,

$a_0 = a^0$, $g_0 = g^0$, and $p_0 = p^0$; (5)

and terminal stock constraints,

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

The grower's objective in equation (1) is to determine the level of chemical pest controls, introduced biological controls, and cultural controls in each period that maximizes the net present value of plant production throughout the growing cycle. 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 arthropod-pests are assumed to be nonincreasing. Alternatively, benefits from the presence of terminal stocks of arthropod-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 arthropods. Under a less conventional or an organic perspective ($Q_{p_T} \geq 0$), the visual presence of predator arthropods may be interpreted as a benefit because they control arthropod-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 cultural controls. Costs of chemical pest controls, introduced biological controls, and cultural controls are assumed to be a function of purchased inputs and application costs.

The net change in plant quality, arthropod 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: pest feeding decreases plant quality attributes ($f_g^a$<0); pest control decreases arthropod growth ($f_{u1}^g$<0, $f_{u2}^g$<0); pest controls can have a positive indirect effect on plant quality through a reduction in the pest population ($f_g^a f_{u1}^g$ >0, $f_g^a f_{u2}^g$>0); cultural controls can increase plant quality attributes ($f_{u3}^a \geq 0$); 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 cultural controls on the pest.[6] The functional representations in (2)-(4) assume applications of controls occur at the beginning of the period and are immediately effective.[7]

[6] This is a deviation from Hueth and Regev's (1974) pest management model, where it is assumed that a nonpest control input has no effect on the pest population.
[7] See Hueth and Regev (1974) or Marsh et al. (2000) for further insight.

Terminal stock constraints in (6) represent an upper bound of the detectable arthropods 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 arthropod 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.[8] Moreover, the terminal stock constraints for arthropod 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. If available, selective insecticides that target pests (and not predators) can be used to control pest stocks without adversely impacting predator stocks.[9] 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 towards 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

[8] 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.

[9] For example, see SePRO (2002) and Uniroyal Chemical (2002).

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

$$+ \sum_{j\in A} \beta\lambda^{j}_{t+1}(j_t + f^{j} - j_{t+1}) ] + \sum_{j\in D} \beta^{T} \phi^{j} (\bar{j} - j_T), \qquad (7)$$

where the set $D$ is defined as $D=\{g, p\}$. The $\lambda^{j}_{t+1}$ (for $j \in A$) variables measure 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 variables $\phi^{j}$ (for $j \in D$) represent the change in the optimal value of the objective function with incremental changes in the respective terminal stock constraint.

## 2.1 Optimal Paths

In this section we focus on optimal paths of chemical and introduced predator controls because we are concerned with the economic tradeoff between biological and chemical pest controls.[10] The necessary condition for the chemical pest control variable, $u_1$, yields

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

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 pesticides are applied in period $t$. When the marginal benefit is less than the marginal cost, then no chemical pest control will be applied in period $t$. The marginal benefit consists of a direct benefit from decreasing the arthropod-pest population $\left(\beta\lambda^{g}_{t+1} f^{g}_{u_{1t}}\right)$, and an indirect benefit of increasing plant quality attributes by decreasing the arthropod-pest population

[10] 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 (1974) previously addressed necessary conditions for cultural controls. The full set of optimal decision rules is provided in the appendix.

$\left(\beta\lambda_{t+1}^{a} f_{g}^{a} f_{u_{1t}}^{g}\right)$.[11] 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 $(-\beta\lambda_{t+1}^{p} f_{u_{1t}}^{p})$. This chemical control condition was previously discussed in Feder and Regev (1975) and in Marsh et al. (2000).

The necessary condition for introduced predators, $u_2$, yields

$$\left(\beta\lambda_{t+1}^{a} f_{g}^{a} f_{u_{2t}}^{g} + \beta\lambda_{t+1}^{g} f_{u_{2t}}^{g} + \beta\lambda_{t+1}^{p} f_{u_{2t}}^{p}\right) \leq C_{u_{2t}}. \tag{9}$$

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 released in period *t*. The marginal benefit consists of the indirect benefit of increasing plant quality attributes (by decreasing the arthropod populations) ($\beta\lambda_{t+1}^{a} f_{g}^{a} f_{u_{2t}}^{g}$), and the direct benefit from decreasing the arthropod populations ($\beta\lambda_{t+1}^{g} f_{u_{2t}}^{g}$). Additionally there is a benefit (rather than a cost as in equation 8) of increasing the predator population ($\beta\lambda_{t+1}^{p} f_{u_{2t}}^{p}$). The marginal cost of introduced predators is equal to the immediate marginal cost ($C_{u_{2t}}$).

Conjunctively controlling arthropods with chemical or introduced predators initiates control trajectories not analyzed in Feder and Regev (1975), Hueth and Regev (1974), or Marsh et al,. (2000). Optimal trajectories for chemical and biological control can be derived from the first order conditions of the bioeconomic model. There are four

[11] Pest control has two outcomes, it decreases pest population in the current period and it decreases population growth in future periods.

interesting control trajectories from (8) and (9): simultaneous, cycling, single, and no controls. The four cases are discussed below.

Case 1: Simultaneous controls

Simultaneous control arises when $u_{1t}$ and $u_{2t}$ are greater than zero in the same period. In this case, the joint use of chemical pesticides and introduced predators is optimal.[12] Combining (8) and (9) results in a joint use equation:

$$\frac{(\beta\lambda_{t+1}^{a} f_{g}^{a} f_{u_{1t}}^{g} + \beta\lambda_{t+1}^{g} f_{u_{1t}}^{g})}{(C_{u_{1t}} - \beta\lambda_{t+1}^{p} f_{u_{1t}}^{p})} = \frac{(\beta\lambda_{t+1}^{a} f_{g}^{a} f_{u_{2t}}^{g} + \beta\lambda_{t+1}^{g} f_{u_{2t}}^{g} + \beta\lambda_{t+1}^{p} f_{u_{2t}}^{p})}{(C_{u_{2t}})}. \tag{10}$$

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: Cycling controls

Cycling between controls occurs when, for example, $u_{1t}$, $u_{2s}$ and $u_{1v}$ are greater than zero for $t<s<v$ but zero otherwise. For our interests, the control strategy is that of cycling between the use of chemical pesticides and introduced predators. This scenario would occur when equality only holds in equation (8) for period $t$ and $v$, and in equation (9) for period $s$, where $t<s<v$. There may be biological reasons or government regulations that dictate cycling. Cycling may be necessary when the effectiveness of the control that is initially optimal decreases and then increases over time. Importantly, cycling may be

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[12] The labels of some chemical pesticides for control of the pest TU indicate that they can be used in conjunction with predators, including PP (e.g. Floramite SC).

appropriate in pest management settings where a grower is required by regulation not to use consecutive applications of the same chemical control to mitigate pest resistance.

Case 3: Single controls

Single control occurs for chemicals when, for example, $u_{1t}>0$ in any 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 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 solution include the condition where pest populations are low enough that they do not affect plant quality and will not increase to the point that plant quality is affected before sale of the crop. On the other extreme, no control would be optimal in the event that plant quality is so low that it could never meet marketing standards regardless of pest control efforts.

2.2 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.

These conditions enhance insight about tradeoffs between plant quality, visual presence of arthropods, terminal stocks of pests and predators at the end of a production cycle, and expected future net benefits. Consider the terminal stock condition of the single pest $g_T$. The adjoint condition for the terminal value $g_T$ is given by

$$\frac{\partial B}{\partial Q}\frac{\partial Q}{\partial g_T}+\frac{\partial F}{\partial g_T}\leq \lambda_T^g+\phi^g \quad . \tag{11}$$

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 periods.

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

$$\frac{\partial B}{\partial Q}\frac{\partial Q}{\partial p_T}+\frac{\partial F}{\partial p_T}\leq \lambda_T^p+\phi^p \quad . \tag{12}$$

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 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 arthropod, including beneficial arthropods such as introduced predators.[13] Alternatively, educating consumers on the advantages of beneficial arthropods may alter negative perceptions, reducing the decrease in aesthetic benefits due to presence of beneficial arthropods. For instance, if consumers recognize and perceive that introduced pests are beneficial arthropods, $Q_{p_T} \geq 0$, 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 flowering plant with beneficial arthropods.

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 arthropods 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 (increase) in marginal benefits that accrue from additional terminal stocks of predators (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

[13] Sadof and Raupp (1996) suggest that insect presence on ornamental plants is perceived as an indication of lower quality because consumers anticipate future pest outbreaks or aesthetic damage.

expected future net benefits in period *T*. Finally, if growers are not constrained by terminal stocks of arthropods, then the co-constraint variables on the right hand side of (11) and (12) are trivial.

## 2.3 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 (1996).[14] For example, Sadof and Alexander (1993), as well as Sadof and Raupp (1996), calculate aesthetic injury levels for the twospotted spider mite on burning bush. Under this approach, ad hoc 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.

[14] Moffit (1988) provides a good overview of break-even relative to marginal pest thresholds.

### 3. Empirical Model

The floriculture bioeconomic model presented above is applied to the greenhouse production system of ivy geranium, which includes a single arthropod 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 $32.7 million in 2003 (USDA, 2004). 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 et al., 1985).

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 cycle 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.[15]

[15] This simplification is needed to solve the empirical model, however the results still provide practical decision rules for greenhouse growers and allow the focus to be on the pest and introduced predator interactions.

A specific application of the theoretical model to an ivy geranium grower can be specified as:

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

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

$$g_{t+1} - g_t = g_t\left(1 - \frac{g_t}{g_m}\right) i_t^g - \alpha g_t p_t - \theta u_{1t} g_t p_t \tag{14}$$

$$p_{t+1} - p = p_t i_t^p + \omega g_t p_t + u_{2t} g_t \tag{15}$$

and terminal stock condition:

$$g_T \leq \overline{g} . \tag{16}$$

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. (2002). Data and methods are briefly discussed below for each empirical relationship. For further details see also Opit et al. (2002a), Opit et al. (2002b), and Schumacher (2002).

## 3.1 Objective Function

The objective function in (13) represents the discounted returns over variable costs, which are henceforth called profits. The first term, $\beta^T P[a_T(\boldsymbol{g}; N, P)]$, 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 arthropod presence. Plant quality is diminished by feeding of TU, which cause puckering and discoloration of the leaves and decrease overall plant growth. Plant quality at time $T$ appears in the objective function, because 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 cumulative $g_t$:[16]

$$\underset{(0.837)}{a_T = 5.455} + \underset{(0.062)}{0.139N} + \underset{(0.576)}{2.094P} + \underset{(0.026)}{0.030N*P} - \underset{(0.002)}{0.005N^2} - \underset{(0.184)}{0.581P^2} - \underset{(0.004)}{0.009}\sum_{t=0}^{T-1} g_t, \tag{17}$$

(R2=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 cycle, and the cumulative sum of the pest population over the growing cycle.[17] (The numbers in parenthesis directly beneath equation (17) are

[16] A quadratic response to $N$ and $P$ is specified, which is consistent with prior research (Jonas, 2001). One hundred and sixty seven ivy geraniums were grown in a greenhouse with varying rates of N, P and mite density (Margolies et al. 2002). 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.

[17] 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, 2002).

the standard errors, while R2 is the R-square goodness of fit measure.) Opit et al. (2005), Sadof and Alexander (1993), and Boys and Burbutis (1972) 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 customers (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 discounts 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:

$$E(P \mid L_1 < Price < L_2) = \beta' x + \sigma \left[ \frac{\phi_1 - \phi_2}{\Phi_2 - \Phi_1} \right], \tag{18}$$

where $L_1$=lower limit, $L_2$=upper limit, $\beta' x = -16.696 + 2.677 a_T$, $\sigma = .685$, $\Phi_1 = \left[ (L_1 - B' x) / \sigma \right]$, $\Phi_2 = \Phi\left[ (L_2 - B' x) / \sigma \right]$, $\phi_1 = \phi\left[ (L_1 - B' x) / \sigma \right]$, $\phi_2 = \phi\left[ (L_2 - B' x) / \sigma \right]$ (Maddala, 1983). The functions $\phi$ and $\Phi$ are, respectively, the density function and the distribution function assuming a normal distribution. The standard errors for the slope and intercept term of $\beta' x$ are 0.7014 and 0.0912, respectively, and the resulting R2 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 maximum observed U.S. wholesale price.

The second term in the objective function (13) represents the discounted variable costs over the growing cycle, 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 cycle. 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 (Van Lenteren, 2000). Initially, we assume there is no visual aesthetic cost or benefit associated with the presence or absence of pests. However, we later relax this assumption and consider several scenarios to determine the influence of visual arthropod presence on ornamentals and the resulting impact on optimal decision rules.

### 3.2 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 term on the right-hand side of equation (14) is a logistic growth function of the TU. The first term on the right-hand side of equation (15) is a decay function of the PP. The remaining right hand side terms are interactions between TU and PP and chemical controls. These functions are chosen because they are consistent with prior empirical research and allow for stable dynamic solutions (Hanley et al., 1997).

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 et al., 1991). This equation links growers' fertilization decisions to their pest management decisions. The intrinsic growth rate of the PP is represented by the parameter $i^p_t$. The parameter $g_m$ is the TU environmental carrying capacity.

The remaining terms on the right-hand side identify interactions between chemical and predator controls and pest stocks. The term $\alpha g_t p_t$ in equation (14) measures the decline in the TU due to the predator $p_t$ where $\alpha$ is a predation constant. The term $\theta u_{1t} g_t p_t$ in equation (14) measures the decline in the TU population due to application of chemical controls where $\theta$ is a constant. The term $\omega g_t p_t$ in equation (15) measures the increase in the PP population from preying on the pest TU where $\omega$ is a constant. Based on prior research using combined chemical and predator controls, it is assumed that selective application of pesticides is compatible with use of predatory mites

(Trumble and Morse, 1993). The last term in equation (15), $u_{2t}g_t$, deals with the introduction of predators, which increases the PP population.

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

$$g_{t+1} - g_1 = g_t\left(1 - \frac{g_t}{12}\right)(0.013P + 0.188N - 0.008(P*N)) - 0.033g_t p_t - u_{1t}g_t p_t$$

(0.005) (0.066) (0.005) (0.014) (19)

(R2=.30)

and

$$p_{t+1} - p_t = -0.90p_t + 0.009g_t p_t + u_{2t}g_t$$

(0.005) , (20)

(R2=.58)

where all variables are as previously specified and numbers in parenthesis directly underneath the equations are standard errors.[18] The net growth functions are estimated with 234 observations in SAS using the nonlinear ITSUR (iterated seemingly unrelated regression) estimation procedure.[19]

Although the terminal pest stock is bounded in (16), in the scenarios presented below we relax this assumption and consider both a fixed and a free terminal stock condition. The terminal stock condition for the predator is not restricted except for several selected scenarios that are explicitly identified in a section with further scenarios. Examining

[18] The intrinsic growth parameter for predator stocks was restricted to -0.90 based on experimental data, personal consultations with entomologists, and previous research.

[19] The parameter on the interaction of the pest and predator in equation (20) incorporates the effect of the pest population on the predator population (see Canal Wheatley and Boethel, 1992).

fixed and free terminal stock conditions provides economically relevant circumstances with which to compare to other decision rules.

## 4. Analysis and Results

Scenarios of the empirical model are simulated to determine the impacts from changes in initial stocks, terminal stocks, and other parameters in the model. Following Standiford and Howitt (1992), the model is solved as a nonlinear programming problem using GAMS software and the solver, minos5 (Brooke et al., 1988). 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.

### 4.1 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 intervention. 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 9.44 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. (2002) and Opit et al. (2002b).

### 4.2 Chemical and Biological Control Scenarios

Assuming a nonzero damage parameter in the model and high initial infestation of TU of 10.0, seven different scenarios are formulated in the upper half of Table 2. Scenario 1 is the base case from which each of the six remaining scenarios are 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, $\alpha$, 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 reason 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. (2001)).

Results of the seven scenarios are provided in the lower half of Table 2. Initial stocks of predators are 4 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 (except Scenario 5), 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.[20] The seven scenarios resulted in profits ranging from $3.64 to $4.08 per ivy geranium, and plant quality indexes ranging from 9.24 to 9.34.

In Scenario 1, the baseline input price ratio of cost of introduced predators/cost of chemical control is 1.175. The optimal control is simultaneous application of chemical control with a kill rate of 0.90 in period 1 and release of 4.75 predators. The quality index is 9.34, the price is $8.31, and the profit is $4.08/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), the simultaneous combination of 4.75 introduced predators and chemical application with a kill rate of 0.90 in the initial period is the optimal solution. This scenario results in an equivalent quality index and price relative to Scenario 1. The resulting profit per ivy geranium is $4.06 only $0.02 lower than in Scenario 1.

When the upper bound of chemical kill rate is lowered to 0.60 (Scenario 3), it becomes optimal to release 4.0 predators in period 1 along with applying chemical control with a kill rate of 0.60 in periods 1 through 7. This scenario results in a quality rating, price and profit of 9.24, $8.04 and $3.71, respectively. The rating, price, and

[20] We simulated the model with unconstrained levels of N and P which result in similar levels of chemical applications and introduced predators as in Table 2.

profit in Scenario 3 are lower than Scenario 1 and chemical use much more extensive, which is expected with a more restrictive upper bound on the chemical kill rate.

To investigate the sensitivity of the model to initial predator conditions, we set the initial predator population to 2 (Scenario 4). Subsequent results involve applying 4.75 predators and a chemical control with a kill rate of 0.90 in period 1. These results are identical to those in Scenario 1.

Restricting the terminal stock of pests to zero (Scenario 5), results in applying 4.0 predators in period 1, 5.01 predators in period 2, and applying chemical control in period 2 with a kill rate of 0.90. The results from Scenario 5 represent circumstances where there is no tolerance for pests when marketing flowering plants. Scenario 5 results in lower quality, price, and profit relative to Scenario 1. Forty-four cents in lower profit per basket is realized when incorporating the zero terminal stock restriction on pests.

The effectiveness of the predator is reduced by 50% through adjusting the predation parameter $\alpha$ from 0.0324 to 0.0162 (Scenario 6). The controls are to release 4.0 predators in period 1 and apply chemical control in period 1 with a kill rate of 0.90. Scenario 6 results in lower profit by $3.94, nearly identical quality 9.32, and slightly lower price $8.25 relative to Scenario 1.

Increasing the magnitude of the parameter that measures the impact of the pest population on plant quality by 1/3 from –0.009 to –0.014 (Scenario 7) results in the same pest management decision rule as Scenario 1. This change in the negative effect of the pest population on plant quality results in a slightly lower quality, price, and thus profit relative to Scenario 1. The lower profits are not surprising given the pests have a larger negative effect on plant quality and price.

## 4.3 Further Scenarios

Further scenarios (with initial TU of 10 unless otherwise indicated) are examined to better understand the role that introduced predators play in the greenhouse ivy geranium system. In order to analyze the optimal use of biological controls and resulting profitability for a grower producing organic flowering crops we run a simulation assuming chemical controls are not available. With no access to chemical control the optimal decision rule is application of approximately 33 predators in the initial period, which results in a profit of \$2.79 per hanging basket. The profit per ivy geranium is 32% lower than Scenario 1, but this assumes there is no price premium for producing and selling organic flowering crops. From a profit maximizing grower's perspective this scenario suggests that there is no economic incentive to produce organic floral crops without a substantial price premium or incentive. In addition to the scenarios with high initial stocks, an alternative scenario is formulated by lowering the initial pest stock to 3. With a lower initial stock of pests, the quality, price, and profit increases to 9.39, \$8.44, and \$4.14, respectively.

For comparison, we also run a simulation assuming no biological controls. The optimal control trajectory is to apply chemical controls in periods 1, 2, 3, and 4 at a kill rate of 0.90. The quality index, price, and profit are 9.30, \$8.20, and \$4.09, respectively. Profit increases by \$0.01 per hanging basket relative to Scenario 1, but it also requires 3 additional chemical applications in the production cycle.

Next, we explore cycling between chemicals and biological controls as alternative pest management strategies. Interestingly, we find that enforcing either the control sequence {chemical, biological, chemical, and biological} or {biological, chemical, biological, and chemical} during the first four weeks of the production cycle decreases profits to $3.66 and $3.45, respectively. Relative to Scenario 1 (Table 2) this reduces profit per hanging basket by $0.45 and $0.63. Imposing cycling of controls yields profit levels most like those in Scenario 5 (when terminal pest stocks were restricted to zero).

Finally, presuming predators are visibly detected, we investigate potential outcomes from the presence of predators on ivy geranium at sales time of the plant. That is, we compare the conventional view that any arthropod-predators 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 period is negatively perceived by the consumer and the price of ivy geranium is discounted by 10%. This change led to more intensive chemical applications in the control trajectory. In contrast, suppose the presence of predators in the terminal period is perceived as a positive benefit by the consumer and a 10% premium is added to the price of ivy geranium. This change yields less intensive chemical use in the control trajectory. In all, these simulated results provide supporting evidence that educating consumers on the advantages of beneficial arthropods may reduce the frequency of chemical pesticide applications by greenhouse floriculture producers.[21]

[21] To explore the uncertainty about quality when geraniums are sold at the terminal period, the model was re-specified to include a stochastic safety-first constraint (Pyle and Turnovsky, 1970). Preliminary analysis including the safety-first constraint suggested the tendency to drive up the level of the quality index, but the controls remained concentrated around the same application days identified in the deterministic model. An alternative approach as suggested by a referee is to consider an option values approach to this application. We encourage further investigation of both approaches for future research.

## 5. Discussion

In the scenarios reported above we conduct sensitivity analysis to evaluate the effects of changes in parameters or model assumptions 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 (1, 2, 4, 6, and 7) with high initial infestation of pests. The information needed by growers to implement this strategy is compatible with an integrated pest management program that includes frequent monitoring of pest density. Alternatively, cycling between chemical and biological controls led to suboptimal results when comparing grower's profit across the different scenarios.

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 cycle from period 1 through 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 that tends to increase in later periods of the production cycle. 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 cycle and less frequent applications in the later periods of production.

## 6. Conclusion

The motivation for this interdisciplinary research is our interest in developing alternative pest management strategies to prophylactic pesticide applications in ornamental crop production. A conceptual bioeconomic model of greenhouse 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, cycling or no controls using chemical pesticides and/or introduced predators to control for pests. The conceptual model is general enough in nature that it can be applied to production systems other than ivy geranium.

In addition, we examined the expected future net benefits of the pest and predator at the terminal sales period. The visual presence of terminal arthropod stocks, which are traditionally perceived negatively by customers, impacts the optimal decision rule (e.g., 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 predator arthropods for biological control of pests. 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 and discussion of results. Our results demonstrate that growers can optimize profits, while still retaining acceptable aesthetic attributes, and reduce frequency of chemical applications by taking advantage of introduced predators released to control pests. 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 cycling between chemical pesticides and biological controls to manage plant quality and pests in greenhouse floriculture production.

Finally, this research focuses on private imputed costs to the representative greenhouse and it does not quantify the social benefits of the potential reduction of chemical pesticide applications by greenhouse growers. Our results suggest 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:

$$\frac{\partial L}{\partial u_{kt}} = -\beta^t C_{u_{kt}} + \beta^{t+1}\sum_{j\in \mathrm{A}} \beta \lambda_{t+1}^{j} f_{u_{kt}}^{j} \le 0,\ \ \frac{\partial L}{\partial u_{kt}} u_{kt} = 0,\ \ u_{kt} \ge 0 \text{, for controls } k\text{=1,2,3}$$

adjoint conditions:

$\beta \lambda_{t+1}^{a} - \lambda_t^{a} = -\beta \sum_{j\in A} \lambda_{t+1}^{j} f_{a_t}^{j}$ for state variables $j$=$a_t$, $g_t$, $p_t$ for $t$=1,…,$T$-1

Kuhn- Tucker/boundary conditions:

$$\lambda_T^a = \frac{\partial B}{\partial a_T}$$

$$\frac{\partial B}{\partial g_T} + \frac{\partial F}{\partial g_T} \le \lambda_T^g + \phi^g\ ,\ \frac{\partial L}{\partial g_T} g_T = 0$$

$$\frac{\partial B}{\partial p_T} + \frac{\partial F}{\partial p_T} \le \lambda_T^p + \phi^p\ ,\ \frac{\partial L}{\partial p_T} p_T = 0$$

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**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] |
| $\alpha$ | predation parameter | (predators/plant) | .0324[d] |
| $\theta$ | kill parameter | (predators/plant) | 1.0[d] |
| $i^p_t$ | PP intrinsic growth rate | $t^{-1}$ | -0.9[d] |
| $\omega$ | PP growth parameter | $t^{-1}$ | .009[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]Production 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, 2002).

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

| Scenario | 1 Baseline | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| | | | *Assumptions* | | | | |
| Initial Stock of PP | 4 | 4 | 4 | **2** [a] | 4 | 4 | 4 |
| Terminal Pest Stock Restriction | free | free | free | free | **0** [a] | free | free |
| Upper bounds on chemical kill rate | 0.90 | 0.90 | **0.60** [a] | 0.90 | 0.90 | 0.90 | 0.90 |
| $\alpha$ [b] | 0.0324 | 0.0324 | 0.0324 | 0.0324 | 0.0324 | **0.0162** [a] | 0.0324 |
| Pest effect on plant quality | -0.009 | -0.009 | -0.009 | -0.009 | -0.009 | -0.009 | **-0.014** [a] |
| Price Ratio[c] | 1.175 | **.7917** [a] | 1.175 | 1.175 | 1.175 | 1.175 | 1.175 |
| | | | *Results* | | | | |
| Profit($/GIV) | 4.08 | 4.06 | 3.71 | 4.08 | 3.64 | 3.94 | 4.01 |
| Quality Index | 9.34 | 9.34 | 9.24 | 9.34 | 9.25 | 9.32 | 9.32 |
| Price of Ivy Geranium($/GIV) | 8.31 | 8.31 | 8.04 | 8.31 | 8.08 | 8.25 | 8.24 |
| Timing of Chemical[d] | 1 | 1 | 1,2,3,4, 5,6,7 | 1 | 2 | 1 | 1 |
| Chemical Kill Rates[e] | 0.90 | 0.90 | 0.60 | 0.90 | 0.90 | 0.90 | 0.90 |
| Timing of Introduced PP[d] | 1 | 1 | 1 | 1 | 1, 2 | 1 | 1 |
| Introduced PP[f] | 4.75 | 4.75 | 4.0 | 4.75 | 4.0, 5.01 | 4.0 | 4.75 |

[a]Parameter represents change from Scenario 1, which is the baseline. Parameter changes were based on personal consultations with industry experts, as well as academic entomologists and horticulturalists experts.
[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 week in the production schedule.
[e]The percentage of pests killed when chemical pesticides are applied.
[f]The number of predators introduced per GIV.