Economic Thresholds:
An Application to Floriculture

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Abstract: This paper introduces conjunctive optimal pest management and production decision rules applied to the floriculture industry. A grower is faced with optimally controlling multiple pests and applying cultural controls to maximize the expected net present value of benefits within a discrete time framework, subject to biological and marketing constraints.

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Motivation and Objective

The USDA reported U.S. grower cash receipts for floriculture and environmental horticulture crops of $10.9 billion in 1996, which ranked the industry seventh among commodity groups behind only cattle and calves, dairy products, corn, hogs, and soybeans. Floriculture crops, which have been defined as cut flowers, cut cultivated greens, potted flowering plants, potted foliage, bedding and garden plants, accounted for approximately one-third of grower cash receipts for floriculture and environmental horticulture. Floriculture crops are typically grown in a greenhouse under protective cover in a controlled environment. Environmental horticulture, which accounted for the remaining two-thirds of ornamental crops, has been defined as nursery plants such as trees, shrubs, ground covers, vines, fruit and nut plants, bulbs, sod, unfinished plants and propagative material such as cuttings, plugs and seedlings. Environmental horticulture products are predominantly grown outdoors and used for landscaping (USDA). While all states commercially produce floriculture and environmental horticulture crops, this sector ranked in the top five commodity groups in 27 states and in the top ten commodity groups in 42 states in 1996.

The USDA reported 14,308 growers with total greenhouse production area of 654 million square feet for 1998. Since 1993 there has been a trend of increased production area combined with a steady decline in the number of floriculture growers. This decline has been attributed to increased import competition and consolidations to achieve economies of scale, such as contract production with large retail chains. Production of ornamentals has depended heavily on the use of chemical pesticides, due in part to the marketing requirements of floriculture crops. While most agricultural resources have been managed for their yield of food and fiber, floriculture crops have been managed for their aesthetic value, which is diminished by the visual presence of pests, as well as by the damage they cause. Therefore, high quality plants with no pests have been a goal of most floriculture producers. A consumer survey conducted in North Carolina reported that good quality plants were the most important factor in selecting a garden center (Wells, Wilder, and Graham). Respondents to a plant nursery firm survey revealed that increasing salable plants was the most important issue for pest management in Florida ornamental nurseries (Hodges, Aerts, and Neal). These findings indicated that plant quality has been an especially important factor in marketing floriculture products, and that successful management of pests has been a critical factor in achieving this high quality.

Many of the pesticides used by floriculture producers are currently being scrutinized by the EPA through the Food Quality Protection Act and may be restricted or eliminated for use in the near future (Onofrey). Hence, developing economically feasible alternative pest management strategies is becoming increasingly important to the industry. Despite the economic importance of the U.S. floriculture and environmental horticulture industry, there have been few economic studies involving production and pest control for ornamental crops. This paper has multiple objectives; the first is to develop a conceptual bioeconomic model for the floriculture industry that will determine optimal decision rules and economic thresholds within a discrete time framework. The second objective is to present a survey of current entomological literature on pest control thresholds, economic injury levels, and aesthetic thresholds, with special attention to floriculture crops. The third objective is to compare and contrast the conceptual bioeconomic model to entomological pest models presented. Lastly, a specific application to spider mite and thrips control on ivy geranium will be discussed.

Background Information

Three papers relevant to optimal pest control in a dynamic setting are briefly discussed. Hueth and Regev's dynamic optimization model involved a single-pest, single crop interaction with the assumption that pests develop increasing resistance to pesticide as a result of pesticide applications. The resulting decision rules from the discrete time optimization problem indicated that pest controls would not be applied unless the marginal value of chemical control in plant growth and pest growth equals the marginal unit cost of insecticides plus the marginal cost of their use in increasing the pest resistance. This model captured the dynamics of the economic threshold, which varies during a growing season rather than remaining constant as typically presented in entomological literature.

Feder and Regev developed a centralized and decentralized dynamic optimization model addressing the environmental effects of chemical pesticides. In the decentralized model a single decision maker ignored the environmental effects of pesticides as well as their effects on the dynamics of both the total pest and predator population since they were viewed as beyond the decision makers control. In contrast, the central decision-maker considered both the environmental costs of pesticides and their effects on the population dynamics. This model provided an analytical means to access a tax or subsidy so that the decentralized model would result in the same pest control decisions as the centralized model.

Marsh, Huffaker, and Long presented a theoretical and empirical dynamic optimization model which included a single stock of insects that vectors a virus, subject to a quality constraint and population dynamics of both pest and predator. The empirical application suggested that the optimal timing of pesticide application occurred at two specific times during the growing season. After the second application of chemical control, predators provided adequate control of the pest.

The above models provided 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. 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, introduced predators can be used to conjunctively control the visual presence of multiple pests on plants and plant quality. A proposed model in the following section will incorporate introduced predators, cultural controls, and chemical controls in determining optimal pest management decision rules for multiple pests within a discrete time framework for the floriculture industry.

Floriculture Bioeconomic Model

The bioeconomic model is structured to represent the greenhouse production system of a single crop of ornamentals, which includes two pests and two predatory mites. Both pests are assumed to be significant in that they can cause major damage to the ornamental plant. In addition, one pest vectors a virus that can also impair the aesthetics and reduce plant quality directly by feeding. Briefly, background information is provided on floricultural production and marketing. Then a conceptual model is proposed and discussed from which decision rules and economic thresholds are derived.

Floriculture Production and Marketing

Floriculture growers often produce various ornamental crops. In the production process, growers make tradeoffs between cultural controls, such as fertilizer and irrigation, and pest control. Unlike other crops, growers must control pests to keep quality and visual levels of insects (pest and predators) at acceptable levels. For this study, we focus on the greenhouse production of ivy geranium.

Floriculture growers typically produce and target their products to either one of two main distinct markets: (a) mass merchandisers, such as Wal-Mart or Home-Depot or (b) specialty shops, such as local retail florists and upper-end garden centers. Mass merchandisers dominate the ivy geranium market. There is a distinct difference in the characteristics of these two market segments. Products sold in the specialty market are larger plants, which means the plant has been under production longer than those sold to the mass merchandiser. In contrast, plants sold in the mass market are generally smaller and have shorter production periods. This difference in product specification implies different production costs and output prices for the two markets. For the proposed bioeconomic model discussed below, we assume that the grower is producing for a mass merchandiser.

The Model

Optimal management in greenhouse production addresses the issue of controlling multiple pests within a multi-trophic system that is subjected to constraints in the output market from both plant quality and visual presence of insects. The profit-maximizing objective requires the grower to optimally control natural predators and prey, recognizing that plant, virus, prey, and predator stocks are biological capital (Hueth and Regev). The conceptual model closely follows Hueth and Regev, and Marsh, Huffaker, and Long, within a discrete time control framework.

The model involves a single horticulture crop, multiple pests, one of which vectors a virus, and multiple prey-specific predators within the planning horizon of one growing season. The state variables of the system are plant stocks, y_t, virus stocks, v_t, insect stocks, g_{1t}, insect-vector stocks, g_{2t}, and prey-specific predator stocks, p_{1t} and p_{2t} per unit area at time t. The control variables are timing and rate of pest controls, u_{1t}, and cultural controls, u_{2t}, measured per unit area at time t. It is assumed application of both controls occur at the beginning of the period and are immediately effective (see Hueth and Regev).

The net growth rates of the plant, virus, insect pests and predator stocks from t to $t+1$ are modeled as continuously differentiable functions, $f^{i}(\cdot)$ for $i \varepsilon A=\{y, v, g_1, g_2, p_1, p_2)$, where f_i represent partial derivatives. Here, f_{g1}^{y} is the partial derivative of y with respect to g_1. Restrictions on f_i^{i} are as follows: feeding by pest decreases plant growth ($f_{g1}^{y}<0$, $f_{g2}^{y}<0$); viral infection decreases plant growth ($f_v^{y}<0$); insect-vectors increase virus growth ($f_{g2}^{v}>0$); insect-vector predators decrease virus growth ($f_{p2}^{v}<0$); pest control increases plant growth ($f_{u1}^{y}>0$); cultural controls can increase plant growth ($f_{u2}^{y}\geq 0$); pest control decreases insect growth ($f_{u1}^{g1}<0$, $f_{u1}^{g2}<0$); predators decrease pest growth ($f_{p1}^{g1}<0$, $f_{p2}^{g2}<0$); and pesticides can be toxic to predators ($f_{u1}^{p1}\leq 0$, $f_{u1}^{p2}\leq 0$).

The optimization problem consists of a concave benefit function $B(y_t; Z)$, and a convex cost function $C(u_{1t}, u_{2t,}; Z)$, where Z represents exogenous factors in the decision process which may include marketing agreements between a grower and buyer. In addition the model includes $F(g_{1t}, g_{1t}, p_{1t}, p_{2t})$ which represents the expected future net benefits based on the state variables at terminal time T, where $F_{g_{1t}} \leq 0$, $F_{g_{2t}} \leq 0$ and $F_{p_{1t}} \geq 0$, $F_{p_{2t}} \geq 0$. The discount factor is $b = (1+d)^{-1}$, with discount rate d .

The grower's optimization problem is

$$(1)\quad \max_{u_{1t}, u_{2t} \geq 0} \{ b^{T} B(y_T; Z) + b^{T} F(g_{1T}, g_{2T}, p_{1T}, p_{2T}) - \sum_{t=0}^{T-1} b^{t} C(u_{1t}, u_{2t}; Z)\}$$

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

$$(2)\quad y_{t+1} - y_t = f^{y}(y_t, v_t, g_{1t}, g_{2t}, p_{1t}, p_{2t}, u_{1t}, u_2), \qquad t=1,\ldots T-1;$$

(3) $v_{t+1} - v_t = f^{v}(y_t, v_t, g_{2t}, p_{2t}, u_{1t}, u_{2t})$, $t=1,\ldots T-1$;

(4) $g_{1t+1} - g_{1t} = f^{g1}(y_t, g_{1t}, g_2, p_{1t}, u_{1t}, u_{2t})$, $t=1,\ldots T-1$;

(5) $g_{2t+1} - g_{2t} = f^{g2}(y_t, g_{1t}, g_{2t}, p_{2t}, u_{1t}, u_{2t})$, $t=1,\ldots T-1$;

(6) $p_{1t+1} - p_{1t} = f^{p1}(y_t, g_{1t}, p_{1t}, u_{1t}, u_{2t})$, $t=1,\ldots T-1$;

(7) $p_{2t+1} - p_{2t} = f^{p2}(y_t, g_{2t}, p_{2t}, u_{1t}, u_{2t})$, $t=1,\ldots T-1$;

a quality constraint (which is defined below),

(8) $Q^* < Q(T) = \bar{q} - \sum_{j=0}^{T-1} n(j)$

initial stocks,

(9) $y_0 = y^0, v_0 = v^0, g_{10} = g_1^0, g_{20} = g_2^0, p_{10} = p_1^0$ and $p_{20} = p_2^0$;

and terminal stock constraints,

(10) $g_{1T} \le \overline{g_1}, \; g_{2T} \le \overline{g_2}, \; p_{2T} \le \overline{p_1}$, and $p_{2T} \le \overline{p_2}$.

The grower's objective in equation (1) is to determine the level of pest controls and cultural controls in each period that maximize the net present value of plant production throughout the growing season. The biological functions of the model, equations (2)-(7), are designed to structure the floriculture problem discussed above (see Appendix for further details). Initial stocks in (9) are necessary to identify unique trajectories of the state variables.

The cost function $C(u_{1t}, u_{2t}; Z)$ is a function of exogenous factors such as input prices, and the level of pest and cultural controls. Pest controls may consist of chemical pesticides, biological controls or a combination of both. Cultural controls include inputs such as fertilizer, water, and growth promoters. Costs of pest and cultural controls are a function of labor costs and may depend on the method of pest control(s) selected. The use of biological controls may be more labor intensive than chemical pesticides since it may require more time devoted to scouting for pests. In addition, the use of biological controls may require sampling of both prey and predator populations, which can increase the marginal cost of bioeconomic control. The cost function should reflect not only the standard per unit costs, but also take into account the differences between biological pest controls and chemical pesticides.

The quality constraint in (8) is needed to link the grower's pest control decision to marketing arrangements between growers and merchandisers. This constraint imposes a lower bound, Q^*, on the quality $Q(T)$ throughout the growing season and an upper bound on quality without pest damage, $\bar{q}$ throughout the growing season. The quality constraint is suitable for the ivy geranium market because there is no alternative outlet for ornamental plants that do not meet quality specifications in the mass merchandise market.[1] Following Marsh, Huffaker, and Long, the decrease in quality throughout the growing season is measured by $n(t) = n_t(v_t, g_{1t}, g_{2t}, p_{1t}, p_{2t}, u_{1t}, u_{2t}: Z)$, which is a continuously differentiable, nonnegative function. It is assumed that the first partial of n_t with respect to g_{1t}, g_{2t}, and v_t is greater than zero, quality degration increases with increments of insect pest stocks or virus stocks. The first partials of n_t with respect to p_{1t}, p_{2t}, u_{1t}, and u_{2t} are assumed to be less than zero, quality degration decreases with increments in predator stocks, pesticides, and cultural controls.

Terminal stock constraints in (10) represent the minimum level of detectable insects on plants that are acceptable to consumers purchasing ornamental plants. The terminal stock constraints depend on the type of the 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 nearly zero. Alternatively, if the plant is purchased for outside aesthetics, desired terminal stocks may be greater than zero. Moreover, the terminal stock constraints for insect stocks, $\bar{g}_1$, and $\bar{g}_2$ may be greater than or equal to zero depending on the 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. Further, controlling stocks of predators, $\overline{p_1}$, and $\overline{p_2}$, requires different strategies relative to pest stocks. In fact, restricting terminal stocks of predators, $\overline{p_1}$, and $\overline{p_2}$, near zero may not be optimal from a grower's perspective.[2]

The Lagrangian function of the discrete time optimization problem in (1)-(7), including the terminal stock constraint, (10) is

$$(11)\ L^{*} = b^{T}(B(y_T; Z) + F(g_{1T}, g_{2T}, p_{1T}, g_{2T})) + \sum_{t=0}^{T-1} b^{t}\,[-C(u_{1t}, u_{2t}; Z) + \sum_{j\in A} b\, l^{j}_{t+1}(j_t + f^{j} - j_{t+1})\,] + \sum_{j\in B} b^{T} f^{j}\,(\overline{j} - j_T)$$

where B={g_1, g_2, p_1, p_2}. Including the quality constraint in (8), the Lagrangian becomes

$$(12)\ L = L^{*} + b^{T} g\,(Q(T)-Q^{*}).$$

The l^{j}_{t+1} (for $j\in A$) variable measures the effect of an incremental change in the respective state variables, (plant, virus, preys, and predators) at time *t* on future benefits in the terminal period *T*. The variable f^{j} (for $j\in B$) represents the change in the optimal value of the objective function with incremental changes in the respective terminal stock constraint. The variable g represents the changes in the optimal value of the objective function with incremental changes in quality standards.

The necessary condition for the pest control variable, u_1, yields

$$(13)\ (b\ l^{y}_{t+1} f^{y}_{u_{1t}} + b\ l^{g1}_{t+1} f^{g1}_{u_{1t}} + b\ l^{g2}_{t+1} f^{g2}_{u_{1t}}) + b\ l^{v}_{t+1} f^{v}_{u_{1t}} + b^{T-t} g\ Q_{u_{1t}} \leq C_{u_{1t}} - b\ l^{p1}_{t+1} f^{p1}_{u_{1t}} - b\ l^{p2}_{t+1} f^{p2}_{u_{1t}}$$

The planning rule in (13) indicates that the marginal benefits from pest control must be less than or equal to the marginal cost of pest control. The marginal benefit consists of the benefit from increasing plant growth and decreasing the insect populations ($b\ l^{y}_{t+1} f^{y}_{u_{1t}} + b\ l^{g1}_{t+1} f^{g1}_{u_{1t}} + b\ l^{g2}_{t+1} f^{g2}_{u_{1t}}$)

plus the marginal benefit of reducing yield loss from viral infection $(b\ l_{t+1}^{v} f_{u_{1t}}^{v})$ and increasing plant quality ($b^{T-t} g\ Q_{u_{1t}}$) due to incrementally increasing u_{1t}. The marginal cost of pest control is equal to the immediate marginal cost ($C_{u_{1t}}$) plus the marginal cost of pest control on natural predators ($-b\ l_{t+1}^{p1} f_{u_{1t}}^{p1} - b\ l_{t+1}^{p2} f_{u_{1t}}^{p2}$).[3]

The necessary conditions for the terminal period, *T*, identify the circumstances under which the optimal trajectories of the model diverge from those of previous studies. For interpretation, we focus on a single pest $g_{1\mathrm{T}}$. The adjoint condition for the terminal value $g_{1\mathrm{T}}$ is given by

$$\frac{\partial F}{\partial g_{1T}} \leq l_T^{g_1} + f_T^{g_1} \tag{14}$$

The left-hand side is the change in the expected future net benefits at time *T* with respect to an incremental change in $g_{1\mathrm{T}}$. The right hand side is sum of the co-state and co-constraint variables for the terminal stock $g_{1\mathrm{T}}$. Hence, (14) implies that the marginal change in the expected future net benefits in period *T* is less than or equal to the marginal benefit due to an incremental change in $g_{1\mathrm{T}}$ plus the marginal benefit of an incremental change in the terminal stock constraint, $\overline{g_1}$. This condition implies that if the terminal stock constraint is not binding then $f_T^{g_1}$ is equal to zero. In contrast, when the constraint is binding there is an incremental benefit of $f_T^{g_1}$ due to increase in the terminal stock constraint. The implication of this condition is that appropriate specification of the terminal stock constraint is an important element in the bioeconomic model since it directly impacts the optimal decision rules. When the terminal stock constraint is binding an artificially low terminal stock constraint may lead to inefficient pest controls, where as an artificially high one can yield a low quality plant that is not marketable.

Next, we briefly review the entomological literature on economic thresholds. Then the pest control decision rule defined in (13), and economic thresholds derived from it, are compared to a selected entomological decision rule. The purpose of doing this is to reconcile, if possible, the underlying assumptions that exist between the rules.

Entomological Models

Entomologists have been applying the concept of economic injury level (EIL) since Stern et al. introduced the concept in 1959. The EIL was defined as the lowest population density of pests that will cause economic damage, with economic damage being defined as the amount of injury that will justify the cost of control. Unfortunately, these concepts did not provide a decision rule for determining when to apply controls. To address the central issue of when to apply controls, a related concept, economic threshold (ET), was introduced. Economic threshold was defined as the population density at which control measures should be initiated to prevent an increasing pest population from reaching the EIL (Stern et al.) From an economic perspective these concepts are somewhat ad hoc in that the decision rule is not derived from axioms of economic behavior.

Pedigo, Hutchins, and Higley presented a modified version of an EIL model, initiated by Norton, as the mathematical expression,

$$EIL = \frac{C}{V \cdot I \cdot D \cdot K} \tag{15}$$

where EIL is the number of injury equivalents per production unit, *C* is the cost of the management activity per unit of production, *V* is the market value per unit of production, *I* is the injury units per insect per production unit, *D* is the damage per unit of injury, and *K* is the proportionate reduction of the insect population due to applying controls. The EIL has been presented as a simple function of four primary variables *C*, *V*, *I* and *D*, but complexity arises when calculating these variables. In particular, injury and damage have been described as function of complex biological processes.[4]

As mentioned above, Stern et al. defined ET in terms of pest population density. In contrast, Pedigo, Hutchins, and Higley defined the ET as the time to initiate control (when future pest injury will cause economic damage), and pest population levels were used as an index of that time. When measuring the EIL and ET in terms of population levels, the ET may be lower or equal to the EIL. If pest control measures were determined to be effective immediately on application, then the ET and EIL were considered to be equivalent. Regardless, understanding and predicting pest population dynamics has been emphasized as essential in determining economic thresholds.

Sadof and Raupp suggested the use of a hybrid EIL to measure subjective attributes that are relevant when marketing and pricing ornamental crops, such as form, texture, color, or quality. The primary difference between the previous model and the hybrid model is that aesthetic quality of the plant is the primary consideration when calculating the value and damage coefficients. Due to the qualitative nature, several methods have been used to establish subjective decision-making rules, for example expert estimation, market surveys, and contingent valuation.

In a study by Raupp et al., the majority of survey respondents indicated a low level of tolerance for pests and damages that they cause. This low level of tolerance should be considered when determining the amount of damage that is acceptable to customers, but misunderstanding the dynamics of economic threshold may result in an artificially low threshold for pests. If the true economic threshold, which may vary over time, is lower than an estimated single static threshold, chemical pesticides may routinely be applied, especially for high value crops. However, if biological control alone or combined with chemicals can be effective, this hybrid model could be used to justify releases of natural enemies on ornamental crops.

Brown presented an addition and variation to the EIL model, suggesting a mathematical expression for the ET incorporating the use of naturally occurring predators to control pests. Brown proposed two types of models. One involved a single pest population that was closely coupled to a predator and host plant. The coupling suggested a nonlinear relationship between pest and predator populations in which the effectiveness of the predator in controlling the pest populations was dependent on both the predator and pest population levels. The second, uncoupled model involved populations of general predators since they were not coupled to any one prey population. Brown's model extended Pedigo, Hutchins, and Higley model with the addition of predators as potential control for pests.

Comparing Decision Rules

Decision rules derived from first order condition of equation (13) provide optimal timing of application of pest control for a profit-maximizing floriculture producer. The planning rule in (13) indicates that control variable, u_{1t}, will not be applied unless the marginal benefit of the control equals the marginal cost of the control at time t. These decision rules are dynamic in nature and take into account the economic and biological constraints of the system. Due to the dynamic nature of plant, predator, prey and virus stocks, the incorporation of time within the bioeconomic model is necessary to identify efficient levels of pest control.

To provide a comparison of the decision rules in (13), we focus on the Pedigo, Hutchins, and Higley modified version of an EIL model in (15):

$$EIL \cdot V \cdot I \cdot D \cdot K = C \qquad (16)$$

This is loosely interpreted, as the benefit of applying pest controls equals the cost of the controls. However, when comparing equation (16) to the first order condition, equation (13), there are several important differences. The first notable difference is that equation (13) from the bioeconomic model is derived from economic theory of profit maximization. The first order condition (13) demonstrates the economic concept that marginal benefits must equal marginal costs in order to initiate control. In contrast, equation (16) does not employ the use of marginal conditions to define pest control decision rules. It simply indicates that the economic benefit from reduction of pests (the left-hand side of the equation) is equal to the cost of the control (C).[5]

Another important distinction between the two decision rules is the issue of intertemporal dynamics. Decision rules can be derived from equation (13) to determine the optimal pest control for each time period from t to T-1, implying that the economic threshold varies with time and pest control levels vary with time. In contrast the decision rule in (16) is static, implying the economic threshold is constant and a single application is applicable.[6]

The third difference in the two decision rules relates to quality. The bioeconomic model imposes a quality constraint, equation (8), which restricts pest control decision rules to ones that will result in plant quality greater than the minimum marketing standard. Equation (16) attempts to captures quality through (V), the market value of the plant. However, without a quality constraint, pest decision rules derived from equation (16) does not guarantee that minimum marketing standards will be met. With these differences in the two models, solving for optimal decision rules from equation (13) will not yield the relationship described in equation (16).

The economic threshold of when to apply pest control occurs when the marginal benefit of the control is equal to the marginal cost of the control. It generalizes the entomological thresholds that identify the EIL as the population density of pests that will cause economic damage and ET as the population density for which a given control should be implemented to prevent pest levels from reaching the EIL level. Interpreting EIL and ET in terms of economic thresholds suggests that no amount of economic damage is tolerable. However, without a clear definition of economic damage, the threshold as defined by entomological literature is not easily determined. An interesting aspect of the entomological threshold model is that it provides a greater understanding of biological relationships often ignored in economics. For example, (D) and (I) in equation (15), which measure damage and injury to the plant are important components of the plant net growth function. These relationships are likely to provide unique insight into specifying equations (2)-(7).

Conclusion

In this paper we developed a conceptual bioeconomic model for the floriculture industry to determine optimal decision rules and economic thresholds within a discrete time framework. The proposed theoretical model was structured for an empirical application to ivy geranium, but was generally specified in that it can also be applied to vegetable crops that are grown in a controlled greenhouse environment. In addition, both a survey of entomological literature on economic thresholds and a comparison of decision rules between models were presented. The optimal decision rule (13) derived from the dynamic bioeconomic model imply that controls would not be implemented unless the marginal benefit of the control equals the cost of control. This generalizes the decision rule (15), which assumes the decision-maker is exogenous and is static in nature. Entomological pest control models have focused more on the biological relationships and the practical aspects of pest management, while excluding economic processes. Multi-disciplinary research in floriculture may provide specific and measurable decision rules that are not only optimal, but are also practical to implement.

The use of biologically-based control for pests on ornamentals is not widespread in the United States. The lack of use of biologically based controls may be due to economics, practicality, lack of education in adopting this technology, risks associated with this technology or any combination of these factors. The conceptual model proposed in this paper identifies the economic and biological processes required to construct a greenhouse grower's decision problem. Developing a conceptual model is a necessary first step to identifying relationships and parameters in order to specify an empirical control model.

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Appendix A: First-Order Conditions

To maximize the objective function in (1) equations (2)-(7) must be satisfied in addition to the following:

maximum conditions:

$$\frac{\partial L}{\partial u_{1t}} = - b^{t} C_{u_{1t}} + b^{t+1} \sum_{j \in \mathrm{A}} b \; l^{j}_{t+1} f^{j}_{u_{1t}} + b^{T} g \, Q_{u_{1t}} \leq 0, \;\; \frac{\partial L}{\partial u_{1t}} \; u_{1t} = 0, u_{1t} \geq 0 ,$$

$$\frac{\partial L}{\partial u_{2t}} = - b^{t} C_{u_{2t}} + b^{t+1} \sum_{j \in \mathrm{A}} b \; l^{j}_{t+1} f^{j}_{u_{2t}} + b^{T} g \, Q_{u_{2t}} \leq 0 , \;\; \frac{\partial L}{\partial u_{2t}} \; u_{2t} = 0, u_{2t} \geq 0 ,$$

adjoint conditions:

$$b \; l^{y}_{t+1} - l^{y}_{t} = -b \; \sum_{j \in a} l^{j}_{t+1} f^{j}_{y_t}$$

$$b \; l^{v}_{t+1} - l^{v}_{t} = -b \left[l^{y}_{t+1} f^{y}_{v_t} + l^{v}_{t+1} f^{v}_{v_t} \right] - b^{T-t} \; g \; Q_{v_t}$$

$$b \; l^{g_1}_{t+1} - l^{g_1}_{t} = -b \left[l^{y}_{t+1} f^{y}_{g_{1t}} + l^{g1}_{t+1} f^{g1}_{g_{1t}} + l^{g2}_{t+1} f^{g2}_{g_{1t}} + l^{p1}_{t+1} f^{p1}_{g_{1t}} \right] - b^{T-t} \; g \; Q_{g_{1t}}$$

$$b \; l^{g2}_{t+1} - l^{g2}_{t} = -b \left[l^{y}_{t+1} f^{y}_{g_{2t}} + l^{v}_{t+1} f^{v}_{g_{2t}} + l^{g1}_{t+1} f^{g1}_{g_{2t}} + l^{g2}_{t+1} f^{g2}_{g_{2t}} + l^{p2}_{t+1} f^{p2}_{g_{2t}} \right] - b^{T-t} \; g \; Q_{g_{2t}}$$

$$b \; l^{p1}_{t+1} - l^{p1}_{t} = -b \left[l^{y}_{t+1} f^{y}_{p_{1t}} + l^{g1}_{t+1} f^{g1}_{p_{1t}} + l^{p1}_{t+1} f^{p1}_{p_{1t}} \right] - b^{T-t} \; g \; Q_{p_{1t}}$$

$$b \; l^{p2}_{t+1} - l^{p2}_{t} = -b \left[l^{y}_{t+1} f^{y}_{p_{2t}} + l^{y}_{t+1} f^{y}_{p_{2t}} + l^{g2}_{t+1} f^{g2}_{p_{2t}} + l^{p2}_{t+1} f^{p2}_{p_{2t}} \right] - b^{T-t} \; g \; Q_{p_{2t}}$$

Kuhn- Tucker/boundary conditions:

$$l^{y}_{T} = \frac{\partial B}{\partial y_T} , \;\; \frac{\partial F}{\partial v_T} = l^{v}_{T} , \;\; \frac{\partial F}{\partial g_{1T}} \leq l^{g_1}_{T} + f^{g_1}_{T} , \;\; \frac{\partial L}{\partial g_{1T}} g_{1T} = 0 , \;\; \frac{\partial F}{\partial g_{2T}} \leq l^{g_2}_{T} + f^{g_2}_{T} , \;\; \frac{\partial L}{\partial g_{2T}} g_{2T} = 0 ,$$

$$\frac{\partial F}{\partial p_{1T}} \leq l^{p_1}_{T} + f^{p_1}_{T} , \;\; \frac{\partial L}{\partial p_{1T}} p_{1T} = 0 , \;\; \frac{\partial F}{\partial p_{2T}} \leq l^{p_2}_{T} + f^{p_2}_{T} , \;\; \frac{\partial L}{\partial p_{2T}} p_{2T} = 0$$

$$b^{T} g \left(Q(T) - Q^{*} \right) = 0$$

Appendix B: Application to Ivy Geranium

The floriculture bioeconomic model presented above will be applied to the greenhouse production system of ivy geranium (*Pelargonium peltatum* (L.)'Her ex Ait), which includes two pests and two predatory mites. The two pests are the twospotted spider mite, *Tetranychus urticae* Koch, and the western flower thrips, *Frankliniella occidentalis* (Pergande). The two predatory mites are *Phytoseiulus persimilis (P. persimilis)* Athias-Henriot and *Iphiseius* (*Amblyseius*) *degenerans* Berlese, that have potential for effective biological control of spider mites and thrips, respectively.

Twospotted spider mite

The twospotted spider mite is a significant pest to many ornamentals, including ivy geranium (Colijn and Lindquist). Spider mites are very small, but because of their rapid reproductive growth potential they can infest and kill entire plants in a short period of time (Sabelis). Under ideal conditions the twospotted spider mite developmental time is approximately 7 days with population doubling times of 2-3 days (Osborne, Ehler, and Nechols). Two major problems associated with controlling the twospotted spider mite are pest resurgence and increasing pest resistance to chemical pesticides. These factors suggest that biological control combined with cultural practices and selective application of pesticides may be an economically optimal pest control strategy for spider mites.

Western Flower Thrips

The western flower thrips is also a major problem in many ornamental crops (Sunderland, et al.). Although thrips feed on plant tissue, their role as a vector of tospoviruses is also of great concern. Thrips must feed on infected plant tissue during their larval stage to become infective, but both larvae and adults can transmit the virus once they are infected. The virus can cause leaf spots, but often obvious signs of the virus are not visible even though the virus reduces overall growth of the plant (Sunderland, et al.). Thrips are resistant to a wide range of pesticides which may warrant a pest management program that consists of biologically-based pest controls integrated with selective used of pesticides.

Plant Growth, Prey and Cultural Relationships

Plant growth is often measured by dry plant weight, but since aesthetics is critical when marketing ornamental crops, a visual index is more appropriate for determining quality of ivy geranium. An index ranking of 1-10 will be used for measuring quality with Q*= 7, the minimum acceptable quality in order for price to be greater than zero, and $\overline{q}$ =10 as the upper bound on quality.

In the absence of pests, ivy geranium plant growth has a quadratic response to one cultural control, nitrogen (Williams and Jonas). However, the addition of spider mites, thrips, tospoviruses, and pesticide controls makes the net plant growth function much more complex. Feeding of spider mites and thrips, and infection by the tospovirus diminishes plant growth. In addition to reducing plant growth, spider mites, thrips and the tospovirus causes petal and foliage deformation, discoloration, and leaf spots, all of which can potentially reduce the aesthetic value of the flower (Brodsgaard; Sabelis).

The amount of damage to the flower caused by spider mites, thrips and tospoviruses depends on pest population levels, water and nutrient status, and stage flowering, which is time dependent. The damage spider mites and thrips inflict on plants is related to the water status and nutrition levels of the host plant. Twospotted spider mite population densities were found to be positively related to the level of drought stress on chrysanthemums (Price, Harbaugh, and Stanley) and schefflera (Colijn and Lindquist) over a range of moisture conditions expected in a greenhouse environment. However, the effect of water status on pest population levels appears to also be dependent on nutrient concentration in plant tissue (English-Loeb). Spider mite reproduction is positively related to plant nitrogen (Wermelinger, Oertli, and Delucchi), while drought stress may increase the susceptibility of plants to mites due to higher concentration of nitrogen in plant tissue.

The positive relationship between fertilizer and pest population levels has important implications in pest management decisions. Fertilizer is a relatively inexpensive input that is typically over-applied, which results in high plant nitrogen levels that spider mites and thrips may prefer. These interactions between plant growth, pest populations, and water and nutrient levels demonstrate the potential for biologically-based pest management in a greenhouse environment, where fertilization, irrigation, pests and pesticide controls can be closely monitored.

Pest and Predator Dynamics

The population dynamics of spider mites and their predatory mite *P. persimilis* can be quite complex. Reproduction of spider mites varies with environment, with temperature being the most important factor that influences their reproductive rate. Similarly, temperature, as well as prey density, is a significant factor in *P. persimilis* development rate. Over a range of 59-86 degrees Fahrenheit, predator populations are able to increase at a faster rate than spider mites (Osborne, Ehler, and Nechols). Because of this, predator populations are able to eliminate local spider mite populations, but in order to survive, the predators must be able to disperse and find new colonies of spider mites. Factors that affect the dispersal of predators include plant density, prey distribution and density, and predator density. When ivy geranium are spaced densely enough so that their leaves touch, the predator can disperse readily. In contrast, when plants have little physical continuity, the predator’s ability to disperse can be reduced by approximately 70 percent (Osborne, Ehler, and Nechols). When prey density is low relative to predators, adult predators disperse in search of a new food source. Timing is critical because applying or introducing predators too late can result in a large amount of pest damage, and releasing them too early causes the predators to starve. The most effective control may require frequent augmentative release of *P. persimilis*. Once spider mite population levels reached high densities, the use of *P. persimilis* to control the mites has not typically been successful. In addition, many pesticides used to control spider mites can disrupt the predator-prey interaction by killing the predator as well as the pest. However, selective use of pesticides can drastically reduce this disruption (Osborne, Ehler, and Nechols).

The predatory mite *I. degenerans* has been found to have potential in controlling thrips populations in greenhouse trials by Van Houten et al. Some of the predatory features of the *I. degenerans* that makes it a promising candidate for biological control of thrips are its predation and reproduction capacities and the absence of diapause (Van Houten, et al.). Prior research has shown that predatory mites will not provide adequate control if they are introduced too late (Brodsgaard). If thrips population levels reach levels that are damaging to ornamentals, biological control is typically not successful. This implies that the use of the *I. degerneran* as control for thrips may involve prophylactic introduction of beneficials before the thrips population reaches a damaging level along with regular scouting for pests during the growing season. Introduction of beneficials on very young plants may also result in the need for relatively fewer predators to control thrips compared to later stages in the ornamental production cycle.

Endnotes

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[1] Discussions with growers in floricultural production indicate that they target an acceptable level of marketable plants for each production period. For example, given the cost structure of a specific firm, 90% of their plants may meet or exceed quality standards and are therefore sellable.

[2] Many consumers seem to have a low tolerance level for any type of insect. Educating consumers on the advantages of beneficial insects may alter this perception. For instance, if consumers understand that they are beneficial insects that do not harm the plant a higher tolerance level may be acceptable.

[3] The necessary condition for the cultural control variable, u_2, can be similarly interpreted.

[4] Applications or variations of the Norton model and the Pedigo, Hutchins, and Higley model have been developed by Brown; Higley and Wintersteen; Sadof and Raupp; Sadof and Alexander; Maltais, Nuckle, and Bland; Sayers et al.; and Cantangui et al.

[5] It is difficult to explicitly compare the functional forms of (13) and (16) because they are based on different underlying assumptions and the functional forms of I, D, and K are not defined.

[6] However, we note that some attempts to integrate biological dynamics into pest control decision rules have been made (Brown).