

OPTIMAL CONTROL OF VECTOR–VIRUS–PLANT INTERACTIONS: THE CASE OF POTATO LEAFROLL VIRUS NET NECROSIS

THOMAS L. MARSH, RAY G. HUFFAKER, AND GARRELL E. LONG

This paper introduces a new specification to the economic pest management literature designed to optimally manage vector–virus–plant interactions for a single crop. The viral, insect-vector, and plant-host stocks are treated as renewable resources and conjunctively controlled in a discrete-time control framework subject to crop quality standards established in marketing contracts. The result is a conceptual integrated pest management model providing optimal insecticide scheduling and dynamic decision-making thresholds in a novel economic pest management context. Model results are compared qualitatively with those from previous specifications. The model is applied empirically to control potato leafroll virus net necrosis in commercial potato production.

Key words: bioeconomic pest control, vector–virus–plant interactions, potato leafroll virus.

The economic pest management literature has focused on controlling a dyadic relationship between insects and crops in which insects cause their major damage directly by physically consuming plants. Accordingly, the literature typically specifies a damage function in which yield loss is related directly to insect population density (see, e.g., Headley, Hall and Norgaard, Feder and Regev, Talpaz and Borosh, Hueth and Regev). In contrast, this article focuses on controlling a triadic vector–virus–plant relationship in which insects cause their major damage indirectly by transmitting a viral pest to crops in the course of predation. While vector–virus–plant interactions have been studied extensively by entomologists, virologists, and other scientists (see, e.g., Harris and Maramorosch 1977, 1980, 1981), they have yet to receive rigorous attention by agricultural economists. The purpose of this article is to extend previous pest planning models to include viral stocks as renewable resources and to examine the impact of vector–virus–plant interactions on a

grower's decision rule and economic threshold levels.

A conceptual Integrated Pest Management (IPM) model is designed to optimize the timing and use of integrated chemical and biological measures to control the vector–virus–plant dynamics regulating crop damage. An optimal decision rule is derived to guide pesticide applications and compared to decision rules from previous studies. The IPM model is applied empirically to manage Potato Leafroll Virus (PLRV) net necrosis in the Northwest potato industry. The results demonstrate how integrating biological controls into the industry's pest management strategy can protect crop quality and yield while sharply reducing insecticide use relative to prophylactic application.

Background

Vector–virus–plant interactions complicate the conceptualization of economic pest management problems in important ways. One way is that crop damage functions must account for processes governing plant infection and crop damage after infection. Plant infection depends upon the population density of insect vectors, the presence of a viral source, and the period over which plants

Thomas L. Marsh is assistant professor in the Department of Agricultural Economics at Kansas State University. Ray G. Huffaker is associate professor in the Department of Agricultural Economics at Washington State University. Garrell E. Long is associate professor in the Department of Entomology, and IPM Coordinator, at Washington State University.

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are exposed to insect vectors. For example, if there is no viral source (e.g., reservoir in seed stock or native plants) to infect insect populations, or there are no insects to vector the virus, then pest control is often not necessary. Alternatively, if a significant source of the virus is present in a field, even small numbers of insects can disseminate the virus throughout the field over time. Viral infections of plants cause crop damage by (a) decreasing yields to an extent depending on climatic factors during the growing season, the physiology of the plants, and a host of other factors (Harris and Maramorosch 1977) and (b) degrading yield quality to an extent depending upon, among other things, the developmental stage of the plant at infection and the time that the virus has to express undesirable side effects in the raw product during storage (Harris and Maramorosch 1981).

Moreover, decision rules and other traditional management tools (e.g., economic thresholds specifying pest levels at which controls should be initiated) must be reformulated to account for vector–virus–plant interactions. In contrast to insect–plant interaction models, economic thresholds include both insect–vector and viral infestations in the field over the growing season. Such thresholds strike an optimal balance between immediate costs of insecticide applications and intertemporal benefits of controlling insect infestation and viral transmission. Benefits include reducing the risk that the virus expresses side effects which degrade the quality of stored raw product below strict quality standards specified in private marketing agreements between growers and processors or specified in government regulations.

The Pacific Northwest potato industry provides an ideal case study to empirically investigate the bioeconomic management of vector–virus–plant interactions causing crop damage. PLRV is responsible for yield and quality losses wherever potatoes (*Solanum tuberosum* L.) are grown, and is one of the most important sources of production risk in the state of Washington (Folwell et al.). The green peach aphid (*Myzus persicae*) (Sulzer) is the most efficient vector of PLRV to potato plants in commercial fields. PLRV causes current-season yield loss in potato plants and may be expressed as net necrosis in tubers (an internal netting of discolored tissue). Not all tubers from an infected plant of a susceptible cultivar develop net necrosis, and those

that do need not develop necrosis at the same time or to the same degree. Necrotic tubers are not suitable for the fresh market or processing, and thus are diverted to lower market-value uses.

Traditionally the potato industry has controlled aphid infestations in commercial fields with a single prophylactic application of a highly toxic systemic insecticide, Aldicarb, at planting to control early season aphid populations, followed by multiple applications of a less toxic foliar insecticide to control mid- and late-season aphid infestations (Hinman et al.). Several alternative pest strategies have been examined in the past but have not proven feasible. For example, controlling aphids by applying chemicals on its overwintering host (peach tree) was discontinued due to environmental concerns (Powell and Mondor 1976; Powell, Maitlen, and Mondor). Similarly, controlling aphids with cultural controls in peach orchards has proven infeasible due to the difficulty of establishing arrangements for cost sharing between potato and peach growers (Folwell et al.).

Unfortunately, there are several disadvantages, both to the grower and society, from continued prophylactic application of insecticides. First, insect pests become resistant to overused insecticides. Second, the strategy disturbs the predator–aphid dynamics in potato fields, leading to pest resurgence and secondary pest infestations (Western Regional IPM Project). For instance, without human intervention, the aphid colonizes the potato field before its natural predators. As predator numbers grow their ferocious feeding habits rapidly crash the aphid population for the rest of the growing season. However, application of systemic and foliar insecticides toxic to natural predators inhibits the predators' ability to keep aphids in check and frequently allows resurgence of aphid numbers. Secondary outbreaks of spider mites also occur in potatoes when natural predators are destroyed. Both aphid resurgence and secondary pest infestations increase the cost of pest control. Third, the prophylactic use of Aldicarb has brought the industry's insecticide practices under extreme scrutiny by state and federal regulators due to its undesirable environmental impacts (*Seattle Post-Intelligencer*). Some of these impacts are ground water contamination (Anderson, Opaluch, and Sullivan; Western Regional IPM Project) and concentration of insecticide residue in food products (National Research Council).

These shortcomings have generated increased producer and public interest in the development of IPM strategies that (a) reduce insecticide use by relying more extensively on the aphid-vector's natural predators, (b) apply insecticides that are relatively nontoxic to natural predators and other beneficial insects, and (c) fine tune the timing of insecticide applications to coincide with periods of the growing season when insects are most efficient at vectoring a virus.

Methodology and Bioeconomic Framework

The optimal management of vector-virus-plant interactions addresses the bioeconomic problem of how to control a multi-trophic-level system, which is linked to, and constrained by, quality standards defined by marketing arrangements. Moreover, it often requires that a grower optimally control natural predators to cope with pest resurgence and secondary pest infestations. Optimal management of the problem is studied best in a capital theoretic framework, recognizing that insect-vector, predator, viral, and plant stocks are durable and costly to adjust (Clark). This article follows Hueth and Regev, and Feder and Regev, by formalizing the conceptual pest problem in a discrete time control framework. This facilitates specification of a corresponding empirical problem to be solved in a nonlinear programming framework (Canon, Cullum, and Polak), which allows the incorporation of complex biological processes in a dynamic optimization context (Standiford and Howitt).

The intraseasonal planning model is specified for a single crop and a finite planning horizon extending over the growing season. There is assumed to be a single stock of insects, subjected to natural predation, that vectors a specific virus. The state variables of the system are plant stocks y_t , viral stocks v_t , insect-vector stocks g_t , and predator stocks p_t , per unit area at time t . The control variable is the timing and rate of insecticide applications, u_t , measured per unit area at time t .

The net growth rates of the renewable resource stocks from t to $t + 1$ are defined as continuously differentiable functions, $f^i(\cdot)$ for $i \in A = \{y, v, g, p\}$. Marginal growth rates

are assumed to behave logistically.¹ Other restrictions are the following: viral infection decreases plant growth ($f_v^y < 0$), feeding by insect-vectors decreases plant growth ($f_g^y < 0$), insect-vectors increase viral growth ($f_v^v > 0$), plant stocks increase viral growth ($f_y^v > 0$), insect predators decrease insect-vector growth ($f_p^g < 0$), pest control decreases insect-vector growth ($f_u^g < 0$), and insecticides can be toxic to insect-vector predators ($f_u^p \leq 0$).

Both predation p_t and insecticide control u_t may adjust insect-vector stocks in $[t, t + 1]$ and, in turn, affect the current period interaction with plant and viral stocks. To generalize this concept, an *effective* insect-vector population in $[t, t + 1]$ is defined as $\hat{g}_t = h(g_t, p_t, u_t)$, where \hat{g}_t increases with insect-vector stocks ($h_g > 0$), decreases with predator stocks ($h_p \leq 0$), and decreases with insecticide applications ($h_u \leq 0$). For example, \hat{g}_t may be specified so that p_t and u_t have immediate control at the beginning of $[t, t + 1]$ on insect-vector stocks (see Hueth and Regev). Alternatively, it may be simplified so that p_t and u_t have no current period impact on insect-vector stocks, or $\hat{g}_t = g_t$.

A concave benefit function $B(y_T; Z)$ and convex cost function $C(u_t; Z)$ are adopted, where Z represents exogenous factors in the decision process such as parameters defined in a marketing arrangement between a grower and buyer. To complete the model, let the concave function $F(v_T, g_T, p_T)$ represent the expected future net benefits based on the state variables at terminal time T , where $F_{v_T} \leq 0$, $F_{g_T} \leq 0$, and $F_{p_T} \geq 0$. The discount factor is $\beta = (1 + \delta)^{-1}$, with discount rate δ .

The grower's optimal planning problem is specified as

$$(1) \quad \max_{u_t \geq 0} \left\{ \beta^T B(y_T; Z) + \beta^T F(v_T, g_T, p_T) - \sum_{t=0}^{T-1} \beta^t C(u_t; Z) \right\}$$

subject to the plant, viral, insect-vector, and predator equations of motion

$$(2) \quad y_{t+1} - y_t = f^y(y_t, v_t, \hat{g}_t) \\ t = 0, 1, \dots, T - 1$$

¹ Restrictions on the logistic growth functions $f_y^y, f_v^v, f_g^g, f_p^p$ are greater than, equal to, or less than zero as y_t, v_t, g_t, p_t are less than, equal to, or greater than $0.5y_{max}, 0.5v_{max}, 0.5g_{max}, 0.5p_{max}$, respectively. Here $y_{max}, v_{max}, g_{max}$, and p_{max} are environmental carrying capacities of y_t, v_t, g_t , and p_t , respectively, and the subscripts on f^i represent partial derivatives.

$$(3) \quad v_{t+1} - v_t = f^v(y_t, v_t, \hat{g}_t) \\ t = 0, 1, \dots, T - 1$$

$$(4) \quad g_{t+1} - g_t = f^g(g_t, p_t, u_t) \\ t = 0, 1, \dots, T - 1$$

$$(5) \quad p_{t+1} - p_t = f^p(p_t, u_t) \\ t = 0, 1, \dots, T - 1$$

initial stocks $y_0 = y^0, v_0 = v^0, g_0 = g^0$, and $p_0 = p^0$, and a quality constraint

$$(6) \quad Q^* < Q(T) = \bar{q} - \sum_{t=0}^{T-1} n(v_t, \hat{g}_t; Z)$$

which is defined below.

The grower's objective in equation (1) is to determine the level of pest control each period that maximizes the net present value of crop production over the growing season. Equations (2)–(5) comprise the biological component of the model, and represent a variation and extension of the pest models of Talpaz and Borosh, Hueth and Regev, and Feder and Regev. Talpaz and Borosh investigate pest control for a single crop and single stock of insects, timing insecticides to control costs and density dependent crop damage. Hueth and Regev focus on the conjunctive management of a pest and its associated stock of susceptibility to pesticides. Feder and Regev examine insect-natural predator interactions and environmental effects in pest control. None of the studies address vector-virus-plant interactions as specified in (2)–(5).

In addition to yield loss, virus-plant interactions often are associated with quality degradation of the raw or processed product (Harris and Maramorosch 1977, 1980, 1981, Folwell et al.). Typically, quality standards for key characteristics are specified in marketing arrangements between growers and buyers, and take the form of inequality constraints (Lichtenberg). To link the grower's pest control decision in the field to a marketing arrangement, equation (6) imposes a lower bound Q^* on the quality $Q(T)$ over the growing season. In (6), \bar{q} is the upper bound on quality without pest damage and $\sum_{t=0}^{T-1} n(v_t, \hat{g}_t; Z)$ is the cumulative incidence of quality degradation over the growing season. The continuously differentiable, nonnegative function $n(v_t, \hat{g}_t; Z)$ defines the contribution from the state of the system at time t to quality degradation (see the Appendix for functional properties).

The Lagrangian function of the discrete time problem in (1)–(5) is given as

$$(7) \quad L^* = \beta^T \left(B(y_T; Z) + F(v_T, g_T, p_T) \right) \\ + \sum_{t=0}^{T-1} \beta^t \left(-C(u_t; Z) + \sum_{j \in A} \beta \lambda_{t+1}^j \right. \\ \left. \times (j_t + f^j - j_{t+1}) \right)$$

while the augmented Lagrangian that includes the quality constraint in (6) is

$$(8) \quad L = L^* + \beta^T \gamma (Q(T) - Q^*).$$

In (7), j indexes the state variables, $j \in A = \{y, v, g, p\}$. The $\lambda_{t+1}^j, j \in A$ are the respective co-state variables for the plant, viral, vector, and predator equations of motion. Each measures the effect of an incremental change in the respective state variable at time t on future benefits in the terminal period T . The co-constraint variable for quality is γ , which represents the changes in the optimal value of the objective function with incremental changes in quality standards.

If an insecticide trajectory is to maximize the objective function in (1), then the first order necessary conditions must be satisfied.² The necessary condition for the control variable yields

$$(9) \quad \left(\beta \lambda_{t+1}^y f_{\hat{g}_t}^y h_{u_t} + \beta \lambda_{t+1}^g f_{u_t}^g \right) \\ + \left(\beta \lambda_{t+1}^v f_{\hat{g}_t}^v h_{u_t} + \beta^{T-t} \gamma Q_{u_t} \right) \\ \leq C_{u_t} - \beta \lambda_{t+1}^p f_{u_t}^p.$$

The planning rule in (9) draws out several interesting comparisons relative to economic thresholds derived in previous studies for pest management. The standard insect-plant interaction model yields a threshold that balances the sum of marginal benefits from increasing plant growth and decreasing the insect population, or $\beta \lambda_{t+1}^y f_{\hat{g}_t}^y h_{u_t} + \beta \lambda_{t+1}^g f_{u_t}^g$, with the immediate cost of insecticide control, C_{u_t} (e.g., Hueth and Regev). The product $f_{\hat{g}_t}^y h_{u_t}$ is positive, indicating increasing plant growth. This is because incrementing u_t decreases the effective insect-vector population \hat{g}_t that, in turn, increases plant growth. Extending the insect-plant model

² The complete set of first order necessary conditions are presented in the Appendix.

to include natural predation of the insect expands the threshold to include the marginal cost of insecticides on natural predators, or $-\beta\lambda_{t+1}^p f_{u_t}^p$ (Feder and Regev). In addition, two new terms appear in (9): $\beta\lambda_{t+1}^v f_{\hat{g}_t}^v h_{u_t}$, the marginal benefit attributed to reducing viral infection by incrementally increasing u_t and $\beta^{T-t}\gamma Q_{u_t}$, the marginal benefit from increased quality due to incrementally increasing u_t . In the first term the product $f_{\hat{g}_t}^v h_{u_t}$ is negative, indicating that increasing u_t decreases the effective insect-vector population \hat{g}_t and thereby decreases virus transmission. For a given interval, ignoring these new terms may underestimate marginal benefits from incrementally increasing u_t . Incorporating these terms allows for a more realistic characterization of economic threshold controlling vector-virus-plant interactions.

The inclusion of the term $\beta^{T-t}\gamma Q_{u_t}$ is an important deviation from previous decision rules and merits additional discussion. The term explicitly links variables originating from marketing arrangements to the behavior of the decision maker anticipating insecticide applications. In (6), an informative, albeit simple, quality constraint is imposed. It depicts the case of a high-quality product with price $P_H > 0$ if (6) is satisfied and low-quality with price $P_L \approx 0$ otherwise. The formulation fits the nature of the case study examined in the next section.

Reinterpreting (9) provides further insight into the nature of the grower's intraseasonal decision to apply insecticides and economic threshold values. The left hand side is the marginal benefit and the right hand side is the marginal cost of a pesticide application due to the marginal increase of u_t .³ If the marginal benefit is less than the marginal cost of an application, then no insecticide will be applied on day t , or $u_t = 0$. If an insecticide is applied in $[t, t + 1]$, or $u_t > 0$, then the marginal benefit just equals the marginal cost of an application. By definition, economic threshold values coincide with the event that $u_t > 0$. Thus, by (9) and the remaining necessary conditions, economic thresholds of the vector and virus vary over time and depend upon the set of economic and biological parameters in the production and marketing processes that structure the system.

Interestingly, recent advances in technology are re-balancing the decision rule in (9) by reducing the impact of insecticides on beneficial insect populations. The second term on the right hand side of (9) indicates that broad-spectrum insecticides can be toxic to predators (i.e., $f_{u_t}^p \leq 0$), which often leads to insect resurgence and secondary pest problems (Feder and Regev). IPM programs now promote selective insecticides that are toxic to the insect-vector but not its natural predators ($f_{u_t}^p \approx 0$), thereby increasing predator efficiency and decreasing the marginal cost of an insecticide application.

Empirical IPM Planning Model

The empirical model represents a grower producing a fall crop of Russet Burbank potatoes in Washington's Columbia Basin. Nearly 2/3 of Washington's commercial potato crop consists of Russet Burbank tubers valued at approximately \$300 million per year (United States Department of Agriculture 1994, Washington State Department Agriculture). These potatoes are ideal for storage and processing, but are highly susceptible to net necrosis.

Over 80% of the potatoes produced in the state of Washington are processed (Buteau and O'Rourke). Growers desire contracts with processors to reduce price risk from volatility of the open market and to capture price incentives for potatoes meeting quality standards desired by processors (Potato Association of America Handbook). Preseason production and storage contracts between growers and processors can take several forms. The *direct* contract requires that the grower deliver potatoes to the processing plant immediately after harvest. The *processor storage* contract stipulates that potatoes be kept in the processor's storage facility at the processor's expense, but that the grower retain any storage risk until the potatoes are accepted for processing at the plant. The *grower storage* contract requires storage in the grower's facility at the grower's expense. The grower accepts any storage risk until the tubers are accepted for processing. In the latter two contracts, storage length is often solely determined by the processor.

Potatoes are assumed to be grown under center pivot irrigation that follows an alfalfa rotation and, except for pest management

³The marginal user cost of an insecticide application is $\beta[\lambda_{t+1}^v f_{\hat{g}_t}^v h_{u_t} + \lambda_{t+1}^v f_{\hat{g}_t}^v h_{u_t} + \lambda_{t+1}^s f_{u_t}^s + \lambda_{t+1}^p f_{u_t}^p]$. It is the current value of future gains foregone by the decision to apply a control unit in time t (Hueth and Regev, Feder and Regev).

strategies, under optimal production conditions. Yields, costs, and production scheduling are taken from Hinman et al., where planting occurs in April and is followed by harvest 150 days later. A premium of \$30/acre is added to the seed cost for transgenic potatoes to control the Colorado potato beetle. Storage costs and parameters are taken from Guenther.

The grower's intraseasonal planning problem is specified to maximize the present value of a stream of net returns subject to natural processes and a net necrosis-quality constraint. The state variables are the stocks of green peach aphids per 0.5 m² per day, g_t , and natural predators per 0.5 m² per day, p_t . The fraction of PLRV in the field per day is v_t and the yield at harvest is y_T (cwt/acre). The incidence of tuber net necrosis contributed per day is n_t . The control variable is the timing and rate of insecticide applications, u_t . Hence, the grower is anticipating insecticide applications over the growing season ($t = 1, \dots, T$ days) to optimally control aphids and guard against PLRV net necrosis, with the expectation of storing potatoes with average tuber weight W (grams) for an exogenously determined storage period S (days). An empirical formulation of the conceptual planning problem can be specified as

$$(10) \quad \max_{u_t \geq 0} \left\{ \beta^{(T+S)} P_H [y_T (1 - D(T) - L(S))] - \sum_{t=0}^{T-1} \beta^t [c_u u_t + c_t] - \beta^{(T+S)} c_s S [y_T (1 - D(T))] \right\}$$

subject to

$$(11) \quad g_{t+1} - g_t = g_t \left(1 - \frac{g_t}{g_{\max}} \right) r_t^g - \mu g_t p_t - K(u_t, g_t)$$

$$(12) \quad p_{t+1} - p_t = p_t \left(1 - \frac{p_t}{p_{\max}} \right) r_t^p$$

$$(13) \quad Q^* < 1 - \sum_{t=1}^{T-1} n_t(t, S, W | \Delta v_t) v_t$$

with initial conditions and other parameters defined in Table 1. The objective functional (10) is maximized subject to daily net rates of change of the aphid [equation (11)] and predator [equation (12)] populations and the PLRV net necrosis constraint [equation (13)].

The empirical model is a simplification of the conceptual model, focusing on essential characteristics to control the PLRV net necrosis system. For example, aphid feeding is often not harmful to potato plants (Ro) and is excluded from the above model. The empirical model can be more efficiently solved by taking advantage of both switching functions and the recursive nature of the bio-economic system. Switching functions, based on threshold values of degree-days and days after planting, are used to control the varying periods over which specific biological processes play important roles in the system. Switching functions help define the optimal trajectory to the empirical model, which is a bang-bang type solution (Clark). Given the recursive nature of the biological processes, the system is effectively reduced to aphid and predator state variables that feed into the PLRV net necrosis constraint. Each of the model components is discussed in detail below.

Objective Functional

Initially, the definition of each term in the objective function from (10) is given descriptively and then the terms are defined mathematically in the sections below. The first term in the objective function, $\beta^{(T+S)} P_H [y_T (1 - D(T) - L(S))]$ (\$/acre), measures the discounted revenue that the producer collects after the storage period on day $T + S$, where P_H (\$/cwt) represents the contract price for high-quality potatoes. The parameter y_T is the potato yield (570 cwt/acre) at harvest time $T = 150$ days, and functions $D(T)$ and $L(S)$ measure diminutions in yield occurring over the 150 day growing and storage periods. The function $L(S) = (0.0004)S$ reflects potato shrinkage after S days in storage (Guenther). The function $D(T)$ measures cumulative yield lost over the growing season due to PLRV infection.

The second term in objective functional (10) nets out the discounted costs over the growing season, where c_u (\$/acre/application) is the unit cost of applying insecticides and c_t represents other production costs (\$/acre) at time t . The final term nets out the discounted costs of storing the post harvest yield of $y_T (1 - D(T))$ when the grower operates under a grower storage contract. The parameter c_s (\$/cwt/day) is the unit storage cost.

To optimize the insecticide trajectory for a single grower, we restrict the terminal func-

Table 1. Parameter Values for Empirical Model

Parameter	Description	Units	Value
t	time period	day	1
g_{\max}	aphid carrying capacity	aphids/0.5m ²	900 ^a
r_g	aphid intrinsic growth rate	t ⁻¹	0.0206 ^a
g_0	initial condition for aphids	aphids/0.5m ² /t	1.4 ^a
DD_{\min}^g	initial arrival of aphids into field	degree-days	865 ^a
p_{\max}	predator carrying capacity	predators/0.5m ²	35 ^a
r_p	predator intrinsic growth rate	t ⁻¹	0.0217 ^a
p_0	initial condition for predators	predators/0.5m ² /t	1.0 ^a
DD_{\min}^p	initial arrival of predators into field	degree-days	1149 ^a
μ	predation parameter	(predators/0.5m ² /t) ⁻¹	0.013 ^a
c_s	rent for potato storage facility	\$/cwt/t	0.0014 ^b
c_u	selective aphicide cost per application	\$/acre	15.25 ^c
$\sum c_t$	other production costs	\$/acre	1462.31 ^d
δ	real daily discount rate	t ⁻¹	0.0002
W	expected tuber weight	ounces	7.8 ^e
P_H	contract price received by grower	\$/cwt	5 ^f
Q^*	quality standard for net necrosis free tubers	%	95 ^g

^a Biological parameters were based on findings from Ro, Ro and Long, and Ro, Long, and Toba

^b See Guenther.

^c The selective aphicide cost per acre is from personal communication with various sales representatives in the chemical industry.

^d Hinman et al.

^e Based on field experiment data from Marsh et al. and unpublished field trials.

^f From Schotzko and unpublished contracts between growers and processors.

^g U.S. Department of Agriculture (1983).

tion $F(v_T, g_T, p_T) \equiv 0$. This follows for several reasons. In the Columbia Basin, terminal stocks of aphids in a potato field generally do not survive the harvesting process and do not impact future stocks infesting the field in the next season. Furthermore, the growth of aphid and predator stocks does not follow a calendar basis, but is strongly dependent on physiological time over the growing season (Ro, Ro and Long). Finally, aphids may act as reservoirs for the virus within a growing season, but typically do not survive the winter to carry over the virus to the next growing season. We assume that viral stocks are managed optimally by using certified seed stock and roguing fields and ditches for volunteer plants and weeds that may reservoir the virus.

Aphid–Predator Dynamics

The aphid–predator population dynamics given by equations (11) and (12), respectively, are a discrete time version of a model developed for the upper Columbia Basin region of Washington (Ro, Ro and Long). The first term right hand side (RHS) of equation (11) is a logistic function measuring the daily net growth in the aphid population over a single potato growing season. The parameter g_{\max} is the aphid’s environmental carrying capacity. Because climate plays a major role in development of insect populations, developmental

times of the aphid are commonly measured on a physiological time scale of degree-days, DD_t . The number of degree-days on a given day is obtained by cumulating the excess of the temperature over a minimum temperature for aphid development which is 4 °C. The parameter $r_t^g = (r_g)(\Delta DD_t)$ is a degree-day dependent intrinsic growth rate, where $\Delta DD_t = DD_t - DD_{t-1}$. The aphid component requires that $\sum DD_t > DD_{\min}^g$ before aphids immigrate into potato fields.

The second term RHS of equation (11) measures the daily population decline due to a predator complex p_t , where μ is a predation constant. The predator complex is an index of aphid predators, which is based on the predator’s potential effectiveness to prey at different stages in an aphids’s life cycle. In a theoretical model, the predator complex acts as an idealized predator species in the control of the aphid. In an empirical model, it is useful in establishing a quantitative approach that is an improved predictor of predator–aphid dynamics (Tamaki). Equation (12) is a logistic equation characterizing the dynamics of the predator complex, where p_{\max} is the predator’s environmental carrying capacity and $r_t^p = (r_p)(\Delta DD_t)$ is its degree-day dependent intrinsic growth rate. The predator component requires that $\sum DD_t > DD_{\min}^p$ before predators immigrate into potato fields.

We modify the Ro and Long model by adding the kill function $K(u_t, g_t)$ [third term RHS of equation (11)] measuring the decline in the aphid population due to an insecticide application. The effectiveness of spraying insecticides is assumed to be proportional to the application rate u_t and the current population level, or $K(u_t, g_t) = ku_t g_t$ with constant k . For $k = 1$, the spray rate u_t , or the insecticide effectiveness, can be expressed as the fraction of aphids killed, so that $0 \leq u_t \leq 1$. Following Ro, Long, and Toba, this article addresses the response of aphid–predator dynamics to selective aphicides. Hence, no kill function is added to the predator equation.

Quality Constraint

The expected level of tuber net necrosis given the state of the system at time t is $n_t = n_t(t, S, W | \Delta v_t)(\Delta v_t)$. The variable $\Delta v_t = v_t - v_{t-1}$ is PLRV infection occurring over a single day. The function $n_t(t, S, W | \Delta v_t)$ is a conditional relationship relating the probability that a potato becomes necrotic in storage, given it is from a plant infected in $[t, t + 1]$, where plant age at inoculation is t (days), storage length is S (days), and tuber weight is W (grams).⁴

Following the entomological literature (Hanafi, Radcliffe, and Ragsdale; Flanders, Radcliffe, and Ragsdale), the expected viral transmission at time t is specified as a function of apterous-days, $G(t)$:

$$(14) \quad v_t = 1 / \left(1 + \exp[19.37 - (5.59 \times 10^{-3})G(t)] \right).$$

Here v_t is a continuous variable that ranges from $v_t = 0$ (signifying no infection of the field), to $v_t = 1$ (signifying infection of the entire field). Apterous-days are defined in the following manner. While alate (winged) aphids introduce the virus into the potato field from outside sources, it is their offspring, the apterous (wingless) aphids, that colonize the potato field and are the efficient vectors of PLRV to potato plants (Hanafi, Radcliffe, and Ragsdale; Flanders, Radcliffe, and Ragsdale). The daily population of apterous

aphids, g_t^α , is calculated as a linear function of the total aphid population (Ro):

$$(15) \quad g_t^\alpha = \max\{0, (g_t - 7.06)/1.19\}.$$

Then, apterous-days are calculated as the cumulative sum of apterous aphids per 0.5 m² measured in the potato field over the growing season, or $G(t) = \sum_{i=1}^{t-1} g_i^\alpha$. Equation (14) is derived from a logistic regression model, which was estimated using field data from Thomas and Long.⁵

Following Roosen et al., the function $n_t(t, S, W | \Delta v_t)$ initially was estimated as a logistic regression model. However, preliminary analysis of the data uncovered spatial dependencies between observations in the field experiment data. Hence, specification of the traditional logistic model and previous spatial statistics literature was extended to correct for spatial correlation by geographic region (Marsh, Mittelhammer, and Huffaker; Marsh). This yielded the relationship

$$(16) \quad n(t, S, W | \Delta v_t) = 1 / (1 + \exp(-(-10.70 + 0.24t - (0.22 \times 10^{-2})t^2 + (5.95 \times 10^{-6})t^3 + (1.36 \times 10^{-2})h - (4.90 \times 10^{-5})h^2 - (3.82 \times 10^{-3})W + (2.04 \times 10^{-5})W^2 - (1.44 \times 10^{-8})W^3 + (4.44 \times 10^{-5})(h * t) - (1.684 \times 10^{-10})(h * W^2))))$$

where

$$h(t, S, W) = \begin{cases} S & \text{if } S < s(t, W) \\ s(t, W) & \text{if } S \geq s(t, W) \end{cases}$$

and

$$s(t, W) = \frac{1}{2} \frac{(1.36 \times 10^{-2}) + (4.44 \times 10^{-5})t}{(4.90 \times 10^{-5}) + (1.684 \times 10^{-10})W^2}$$

so that the net necrosis relationship is restricted to be monotonic over the storage period. This deterministic constraint assumes 100% inspection at delivery to the processor, implying that each necrotic tuber can be identified at inspection.

⁴ The biological literature has identified plant age at inoculation, storage length, and tuber weight as being important factors in predicting whether a potato tuber will become necrotic (Rich; Roosen et al.; Marsh et al.).

⁵ Hanafi, Radcliffe, and Ragsdale, as well as Flanders, Radcliffe, and Ragsdale, used ordinary least squares to estimate a viral transmission relationship as a function of apterous aphid-days. Logistic regression is used here to take advantage of the qualitative nature of the data and biological relationship. Applying (14) in this manner simplifies some of the environmental and biological interactions (e.g., temperature) influencing v_t , but yet focuses on the essence of the problem which is the bioeconomic control of the insect-vector.

Viral-Yield Loss Relationship

The function $D(T)$ measures cumulative yield lost over the season from PLRV infection:

$$(17) \quad D(t) = \sum_{j=1}^t (\Delta v_j)(d_j).$$

It accumulates the daily yield loss through period t measured as the product of the daily increase in PLRV infection, $\Delta v_j = v_j - v_{j-1}$, and the percentage daily lost yield due to the increased infection, d_j . The percentage daily yield loss is a continuous valued function defined as

$$d_t = \begin{cases} \begin{aligned} &6.23 \times 10^{-4} \\ &+ (7.12 \times 10^{-3})t \\ &- (8.46 \times 10^{-5})t^2, \text{ if } 0 < t < 85 \end{aligned} \\ -3.67 \\ \begin{aligned} &+ (5.88 \times 10^{-2})t \text{ if } 105 < t \\ &- (2.28 \times 10^{-4})t^2, < 150 \end{aligned} \\ 0, \text{ otherwise} \end{cases}$$

which is based on data reported in Marsh et al. and is similar to the findings of Rich. The percent of yield loss from viral infection over the growing season is highest during the early season, ranging from 0 to 15% over the growing season.

Analysis

Several scenarios were formulated to investigate the PLRV net necrosis system under a variety of bioeconomic circumstances. Generating the planning scenarios proceeded in several steps. First, a no-spray scenario was formulated by omitting the quality constraint to inspect the empirical biological processes of the IPM model without human intervention. This also provided initial trajectories for the other planning scenarios that imposed the quality constraint. Second, the quality constraint was imposed to investigate the impact of contract type, storage length, and average tuber weight on the grower's optimal spray pattern. Third, the impact of pest resurgence on the optimal insecticide schedule was examined. The system was solved as a nonlinear programming model using GAMS/MINOS5 (Brooke, Kendrick, and Meeraus).

An actual degree-day sequence from Othello, Washington, in the Columbia Basin

was used that generates high aphid infestations.⁶ The degree-day sequence begins on January 1 and continues until harvest time in September. Based on distributions of tuber weight from Russet Burbank field trials, the average weight of a harvested tuber was set at 7.8 ounces (with 75% of the tubers ≥ 6 oz). The contract price was set at $P_H = \$5/\text{cwt}$ for high-quality tubers, which constitutes a base price of $\$4.40/\text{cwt}$ and $\$0.60/\text{cwt}$ for meeting size incentives. The price incentive was $\$0.60/\text{cwt}$ if at least 70% of the tubers ≥ 6 oz (Schotzko). Initially, a grower storage contract was assumed with storage length $S = 120$. Model parameters are reported in Table 1.

Scenario 1 (No-spray)

In the absence of the necrosis constraint, a large infestation of uncontrolled aphids rapidly spreads PLRV throughout the potato field. First appearance of aphids in the field occurs fifty-two days after planting with the peak flight of 585 aphids/0.5 m² on day 76. The resulting yield loss ranges from 3 to 5% and the incidence of net necrosis from 25 to 50% for medium to large tubers, respectively. The resulting predator-aphid dynamics are consistent with Ro's continuous-time predator-aphid model, while the other biological results are consistent with observations in commercial fields reported by Rich and Powell and Mondor (1973).

Scenario 2 (Imposition of Quality Constraint)

The quality constraint was set at $Q^* = 95\%$, and compatible with the concept of IPM, a selective aphicide was assumed to be sprayed.⁷ The optimal control pattern concentrates spraying at two times across the growing season. In effect, the spray rate can be interpreted as an optimal kill rate of aphids per day. The first selective aphicide application occurs fifty-two days after planting, optimally taking 82% of the current aphid population. The second spray occurs on day 80 at a rate of 84%. The total aphicide cost over the season is about $\$25/\text{acre}$. Yield loss is inconsequential.

⁶ A degree-day sequence that induces a high aphid infestation is used for the purpose of generating a conservative insecticide trajectory, which can be used as a prudent pest management recommendation to potato producers.

⁷ For example, pirimicarb is a selective aphicide being considered for potato production (Ro and Long).

Spraying on day 52 slows aphid colonization, and then the population is allowed to increase at its natural rate until the second spray on day 80. The second spray is applied at an optimal time and rate to slow aphid growth near its peak flight, enabling the predator complex population to overtake the aphid population. After day 80, the voracious feeding of the predator complex rapidly dominates and the aphid population crashes for the remainder of the growing season. At the second spray the economic threshold level of aphids is $366/0.5 \text{ m}^2$ and of plant infection is 1%. Over the growing season as the exposure time of potato plants to infected aphids increases, and as apterous-aphids reach peak numbers, the predicted PLRV infection level increases logistically. After day 95, the cumulative plant infection level reaches 17.6% and cumulative apterous-days total 3,192.

Scenario 2 was also used to investigate the impact of contract type (i.e., direct, grower storage, and processor storage), various storage periods ($S = 0, 60, 120$ days), and various tuber weight categories (medium-sized tubers $W = 7.8$ and large tubers $W = 18$ oz) on net present value (NPV), the optimal spray pattern, and threshold values. For the purposes of this study the contract type determines whether potatoes must be stored, and thus whether the grower assumes the risk that potatoes will become necrotic in storage. Longer storage periods and larger tuber sizes tend to increase the probability that tubers become necrotic (Roosen et al.; Marsh et al.). Table 2 displays these results, where over the growing season the “aphid” threshold is measured in terms of cumulative apterous-days and the “infected plant” threshold in terms of cumulative percentage PLRV.

The impacts of the various types of contracts are qualitatively similar for the different storage periods and tuber weights. Direct contracts generate the highest NPV because they do not require storage. Processor storage contracts return the next highest NPV because, although the producer bears the risk of stored potatoes becoming necrotic, the processor incurs incidental storage costs. Grower storage contracts return the least NPV because the grower incurs the storage costs along with the risk that stored potatoes become necrotic. The timings of the spray patterns are almost identical for each contract. As before, aphids are sprayed around day 52 to slow colonization and then approximately twenty to thirty days later to slow

aphid growth near its peak flight. Finally, the aphid and infected-plant levels are almost identical for grower and processor storage contracts since the grower bears the storage risk of necrotic potatoes in either. The levels are higher for the direct contract because potatoes are not stored.

The impact of more lengthy storage time shows qualitatively similar patterns regardless of contract type and tuber weight. NPV decreases with storage length due to both the increased probability that tubers will become necrotic before processing and the increased storage costs. There is little or no impact on the timing of spraying patterns, but the kill rate measuring the intensity of each application adjusts to compensate for longer storage periods. Increased storage length decreases both the aphid and infected-plant thresholds as the producer optimally controls against the increased probability of necrosis during storage.

For the most part, the impact of tuber weight is relatively the same across contract type and storage period. Increased tuber weight slightly decreases NPV, which is due to additional pest costs undertaken to counter the increased potential for infected larger tubers to exhibit necrosis. Nor does it significantly change the optimal spraying pattern. Increasing tuber weight adjusts the kill rates and decreases the aphid and infected-plant populations as countermeasures to the increased susceptibility of large tubers to net necrosis in the field and in storage.

Scenario 3 (Pest Resurgence)

To examine the effect of pest resurgence, the planning model was optimized for an increasingly inefficient predator complex (i.e., the predation coefficient μ was decreased over the range 0.022 to 0.004). A grower storage contract of $S = 120$ days and an average tuber weight $W = 7.8$ oz were assumed. A highly efficient predator complex (i.e., $\mu = 0.022$) dominates the aphid population and reduces the number of necessary sprays from two to one. As the predator complex becomes increasingly inefficient, pest resurgence becomes evident over the second half of the growing season and the number of optimal sprays increases from two to eight. The timing of the first two sprays remains similar to those reported in Table 2, but the spraying frequency increases in the mid and late season to combat pest resurgence.

Table 2. Results of Empirical Model with Quality Constraint

	Contract Type				
	Direct	Grower Storage		Processor Storage	
Tuber weight ($W = 7.8$ oz)	$S = 0$	$S = 60$	$S = 120$	$S = 60$	$S = 120$
NPV (\$/acre)	605.12	471.97	343.79	516.58	435.31
Spray timing (days after planting)	52, 75	52, 76	52, 80	52, 76	52, 76
Kill rates (% aphids on spray day)	0.25, 0.92	0.65, 0.86	0.82, 0.84	1, 0.55	0.68, 0.86
Apterous aphid threshold (cumulative apterous-days)	3,472	3,255	3,192	3,255	3,178
Infected plant threshold (cumulative % PLRV)	50.7	23.2	17.6	23.3	16.7
Tuber weight ($W = 18$ oz)	$S = 0$	$S = 60$	$S = 120$	$S = 60$	$S = 120$
NPV (\$/acre)	601.48	471.34	343.13	514.93	434.64
Spray timing (days after planting)	52, 75	52, 77	52, 53, 80	52, 75	57, 77
Kill rates (% aphids on spray day)	0.51, 0.91	0.67, 0.87	1, 0.11, 0.6	0.90, 0.76	0.73, 0.86
Apterous aphid threshold (cumulative apterous-days)	3,157	3,073	3,059	3,073	3,066
Infected plant threshold (cumulative % PLRV)	15.3	9.9	9.3	10.1	9.6

As predation efficiency decreases, the spray patterns start to resemble traditional pest control practices in which insecticides are toxic to predators and multiple sprays are required to keep tuber net necrosis under acceptable levels. The NPV of returns ranges from \$358.22/acre with highly efficient strong predation to \$253.43/acre with minimally efficient predation, a difference of \$104.79/acre. In actual production conditions, the NPV often is driven down further because of secondary-pest outbreaks. In all, ignoring natural predation imposes on the grower an opportunity cost that is positive and large in magnitude.

Discussion

For the given degree-day sequence, the optimal timing of aphid-specific insecticide applications under the IPM strategy targets sprays at the initial infestation of aphids to delay colonization and just after the peak flight of aphids into the potato field. Thereafter, aphid predators protected under the IPM strategy succeed in optimally controlling the

aphid population. The optimality of this strategy is fairly robust as demonstrated by its stability across the variety of planning scenarios investigated.

The IPM insecticide strategy, which costs about \$55/acre (\$25/acre for aphid control plus \$30/acre for Colorado beetle control), is strikingly different from the current prophylactic strategy used by growers, which costs about \$180/acre (Hinman et al.). The current strategy generally involves prophylactically applying a systemic insecticide at planting in April, and three to four later season applications of foliar insecticides in June, July, and August. When vectoring aphids are not in the field, this is an ineffective way to combat PLRV net necrosis. In contrast, when vectoring aphids are in the field, the IPM strategy's optimally timed selective aphicide applications allow natural predators to control aphids for the second half of the growing season. This lessens the impact of pest resurgence and secondary pest problems and, as a result, reduces the number of foliar applications that the current strategy requires over the growing season and reduces the production risk associated with longer storage times. Reducing the number of applications also

avoids the adverse effects of systemic insecticide residue on the environment and human health.

In the upper Columbia Basin, recent IPM demonstration projects in commercial potato production have provided real-world evidence that timing insecticide applications is effective. An effective IPM program for combating PLRV net necrosis should include roguing fields for volunteers and weeds and continued use of certified seed stock to keep sources of PLRV at a minimum in the field. Furthermore the pest management program should include scouting for green peach aphid activity, timing insecticide applications with forecasted aphid flights, and strategic management of storage to prevent incidences of tuber net necrosis. This article facilitates the adoption of such a program by better identifying the timing and rate of insecticide applications over the growing season.

Conclusion

This article is motivated by our disciplinary interest in analyzing a novel pest management application characterized by vector–virus–plant interactions, and by the increasing public pressure to replace current chemically based pest management strategies for controlling viruses in crop production with IPM strategies relying more on biological processes. A conceptual discrete-time control model is developed linking vector–virus–plant interactions, as well as predator–insect dynamics, to output quality in pest control. Optimal timing and rate of insecticide applications and optimal levels of dynamic economic thresholds are derived. Relative to previous pest control models, the optimal decision rule identifies new marginal conditions of insecticide applications in the presence of a viral infection.

The IPM strategy was applied empirically to examine the case of PLRV net necrosis in potatoes. For the given degree-day sequence, the optimal timing of aphid-specific insecticide applications under the IPM strategy targets sprays near the initial infestation of aphids to delay colonization and just after the peak flight of aphids into the potato field. Thereafter, aphid predators protected under the IPM strategy succeed in optimally controlling the aphid population. The optimality of this strategy is fairly robust as demonstrated by its stability across the variety of

planning scenarios investigated. The optimal strategy reduces production risk from longer storage times by reducing the threshold level of aphids and PLRV in the potato field, which lowers the producer's incidence of necrotic potatoes to acceptable levels when delivered to the processor. The IPM strategy also has the potential to decrease adverse effects of insecticide residue on the environment and human health by cutting back on the number of applications.

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Appendix

The functional properties of $n(v_t, \hat{g}_t; Z)$ are that quality degradation increases with increments of viral and insect-vector stocks, or $\partial n/\partial v_t > 0$ and $\partial n/\partial \hat{g}_t > 0$. Then, for example, it follows that quality degradation decreases with increments of insecticide control, or $\partial n/\partial u_t = (\partial n/\partial \hat{g}_t)h_{u_t} < 0$. By (6), this can be extended so that $Q_{v_t} < 0$, $Q_{g_t} < 0$,

$Q_{p_t} > 0$, and $Q_{u_t} > 0$.

The first order necessary conditions of (8) are the maximum principle:

$$\begin{aligned} \frac{\partial L}{\partial u_t} &= -\beta^t C_{u_t} + \beta^{t+1} \lambda_{t+1}^y f_{\hat{g}_t}^y h_{u_t} \\ &+ \beta^{t+1} \lambda_{t+1}^v f_{\hat{g}_t}^v h_{u_t} + \beta^{t+1} \lambda_{t+1}^g f_{u_t}^g \\ &+ \beta^{t+1} \lambda_{t+1}^p f_{u_t}^p + \beta^T \gamma Q_{u_t} \leq 0, \\ \frac{\partial L}{\partial u_t} u_t &= 0, \quad u_t \geq 0 \end{aligned}$$

adjoint conditions

$$\begin{aligned} \beta \lambda_{t+1}^y - \lambda_t^y &= -\beta[\lambda_{t+1}^y f_{y_t}^y + \lambda_{t+1}^v f_{y_t}^v] \\ \beta \lambda_{t+1}^v - \lambda_t^v &= -\beta[\lambda_{t+1}^y f_{v_t}^y + \lambda_{t+1}^v f_{v_t}^v] \\ &- \beta^{T-t} \gamma Q_{v_t} \\ \beta \lambda_{t+1}^g - \lambda_t^g &= -\beta[\lambda_{t+1}^g f_{g_t}^g + \lambda_{t+1}^y f_{\hat{g}_t}^y h_{g_t} \\ &+ \lambda_{t+1}^v f_{\hat{g}_t}^v h_{g_t}] \\ &- \beta^{T-t} \gamma Q_{g_t} \\ \beta \lambda_{t+1}^p - \lambda_t^p &= -\beta[\lambda_{t+1}^g f_{p_t}^g + \lambda_{t+1}^p f_{p_t}^p \\ &+ \lambda_{t+1}^y f_{\hat{g}_t}^y h_{p_t} + \lambda_{t+1}^v \\ &\times f_{\hat{g}_t}^v h_{p_t}] - \beta^{T-t} \gamma Q_{p_t} \end{aligned}$$

transversality conditions $\lambda_T^y = \partial B/\partial y_T$, $\lambda_T^v = \partial F/\partial v_T$, $\lambda_T^g = \partial F/\partial g_T$, and $\lambda_T^p = \partial F/\partial p_T$, complimentary slackness condition $\beta^T \gamma(Q(T) - Q^*) = 0$, and equations of motion (2)-(5).