Journal of Agricultural and Resource Economics 44(3):646–663 ISSN 1068-5502

doi: 10.22004/ag.econ.292336

Phytosanitary Regulation on Washington Apple Producers under an Apple Maggot Quarantine Program

Yeon A Hong, R. Karina Gallardo, Xiaoli Fan, Shady Atallah, and Miguel I. Gómez

We investigate how phytosanitary regulations related to apple maggot could affect optimal pest control strategies and profits for apple producers potentially located in apple maggot quarantine areas. We estimate producer profits by an orchard's quarantine status subject to a phytosanitary regulation requiring an additional cold storage period, reflecting the import requirements of China and British Columbia (Canada). Interestingly, we find that the increased cost burden generated by the additional cold storage from quarantine areas has an unintended consequence of raising the number of chemical applications, suggesting a substitution effect between pesticide application and cold storage.

Key words: bioeconomic model, pest control, phytosanitary trade regulation

Introduction

Agricultural phytosanitary trade regulations of invasive species are designed to prevent the introduction of alien species considered harmful to the domestic agricultural industry (U.S. Department of Agriculture, 2017b). Common practices for preventing the risk of invasion include cleaning a cargo haul and establishing inspection requirements for imported agricultural products (Corn and Johnson, 2013). Such regulations often increase the cost burden to producers and have the potential to reduce trading volumes (Disdier, Fontagné, and Mimouni, 2008). The literature on sanitary and phytosanitary (SPS) regulations quantifies the impact of a technical barrier on market equilibrium and trade, and many studies indicate that SPS standards are becoming significant barriers to international trade of food and agricultural products (Calvin and Krissoff, 1998; Liu and Yue, 2009). For example, a study by Calvin, Krissoff, and Foster (2008) on the costs of the Japanese phytosanitary barriers imposed on U.S. apples exported to Japan shows that eliminating the fire blight protocol could substantially increase the volume and value of Japanese apple imports from the United States. However, this finding should not be taken in absolute terms, as the impact of the elimination of phytosanitary barriers could depend on the degree of substitution between domestic and imported apples, as pointed out by Yue, Beghin, and Jensen (2006).

Yeon A Hong (corresponding author) is a research fellow at the Center for Food and Marketing Research in the Department of Agriculture, Food and Forestry Policy Research at the Korea Rural Economic Institute. R. Karina Gallardo is an associate professor in the School of Economic Sciences, Puyallup Research and Extension Center at Washington State University. Xiaoli Fan is an assistant professor in the Department of Resource Economics and Environmental Sociology, Faculty of Agricultural, Life and Environmental Sciences at the University of Alberta. Shady Atallah is an assistant professor in the Department of Natural Resources and the Environment and the Department of Economics at the University of New Hampshire. Miguel I. Gómez is an associate professor in the Charles H. Dyson School of Applied Economics and Management at Cornell University.
This study was funded by the Washington Tree Fruit Research Commission and by the Washington State University School of Economic Sciences IMPACT Center to investigate Economic Impact of Apple Maggot Infestation. Assistance provided by Suzette Galinato (WSU IMPACT Center Research Associate) is also greatly appreciated.

Review coordinated by Dragan Miljkovic.

The emergence of transnational agricultural organizations, coupled with increased globalized production and distribution systems and the proliferation of free trade agreements, has encouraged the existence of global agricultural markets (Bruinsma, 2017). Global agricultural markets have opened opportunities for U.S. apple producers to expand their businesses beyond the saturated domestic market, increasing export dependency for the apple industry. In 2015, the United States exported 988,500 tons of apples out of the total production of 5,020,000 tons (19.7%) (United Nations, 2016; U.S. Department of Agriculture, 2017c). Notably, the state of Washington—the top apple-producing state in the United States—exported more than 30% of its total production during the same marketing year (Washington State Tree Fruit Association, 2017). The growth of world trade has had a number of environmental consequences, of which one of the most significant may well be the redistribution of pests (Perrings, Mooney, and Williamson, 2010). The opening of new markets and trade routes has resulted in the introduction of new species, either as the object of trade or as the unintended consequence of trade. Indeed, the volume and direction of trade turn out to be good empirical predictors of invasions (Levine and D'Antonio, 2003).

Among the pests affected by trade regulations, the North American apple maggot (*Rhagoletis pomonella*) has received considerable attention in recent years from both producers and regulators due to its invasiveness, the bioclimatic similarity between trading partners, and the volume and composition of trade. Apple maggot attacks apples, cherries, plums, apricots, and pears (Boller and Prokopy, 1976). The main damage is caused by the female fly laying eggs beneath the surface of the host fruit, leaving a puncture wound that results in a sunken spot on the fruit surface. The hatched young larva consumes the flesh of the fruit, leaving a brown trail of rotting flesh and exit holes (Dean and Chapman, 1973). As the damaged fruit usually drops prematurely, orchards infested by apple maggot without a proper treatment could face considerable yield losses (Glass and Lienk, 1971; Howitt, 1993; Sansford, Mastro, and Reynolds, 2016). In the 1970s, apple maggot was regarded as a serious pest in the United States due to its presence in the eastern half of the country and its potential spread to northwestern regions (Ali Niazee and Penrose, 1981). In fact, in the U.S. Northwest, apple maggot is currently under control due to effective management, but attention has recently refocused on the pest due to policy measures that could jeopardize the extent of apple maggot threatened and quarantine areas.

Washington has implemented a quarantine program to prevent apple maggot dissemination and establishment beyond quarantine areas since the early 1980s.[1] Apple producers with orchards in the quarantine areas must comply with pest regulations to export fresh apples (Klaus, 2015a,b).[2] These regulations depend on shipping destinations. For example, the main export markets for Washington State apple operations—China and British Columbia (BC), Canada—require all apples shipped from the United States to be certified as apple-maggot-free. Apples from quarantine areas must be stored at 1°C for an 40 days.

Concerns about the risk of apple maggot dissemination and establishment beyond Washington State quarantine areas are increasing because compost-processing companies have recently established operations in Eastern Washington, increasing the transportation of yard (green) compost waste coming from the Seattle metropolitan area, which is under apple maggot quarantine, to the eastern parts of Washington, which are apple-maggot-free zones. This unprocessed compost has increased the risk of apple maggot infestation in areas that are apple-maggot-free and where the bulk of the Washington apple production industry is concentrated (Sansford, Mastro, and Reynolds, 2016).

In spite of the increased concern about dissemination of the apple maggot, little research has been conducted to examine the economic impacts of the quarantine program on apple producer

[1] Quarantine programs are similar to federal marketing orders in that they require producer participation and compliance in exchange for access to export markets. They are different in that the immediate consequence of quarantine programs—the restrictions—are imposed by the importing entity, as in the case of BC and China, rather than being the result of a grower collective action aimed at preserving the reputation of a commodity (Gray et al., 2004).

[2] Apple maggot quarantine areas are regions in which the pest is considered established but officially being controlled.

control decisions and profits. We investigate how phytosanitary regulations affect the optimal pest control strategy (defined as the number of pesticide applications) for an apple producer under the pest quarantine program and assess their impact on profits. We model the situation in which the apple maggot becomes a serious threat to producers, causing the expansion of quarantine areas to the point where trade flows could be affected due to the existence of phytosanitary regulations.

We develop a representative producer's optimal management problem in a theoretical framework, in which the objective is to maximize profits by choosing an optimal control strategy subject to pest dynamics by quarantine status. The pest infestation level and the related costs differ according to the area's quarantine status. We examine how the producer's optimal choice depends on the area's quarantine status and the existence of international trade regulation of invasive species on fresh apples shipped from quarantine areas. Finally, we analyze the sensitivity of producer profits with respect to increases in trade dependency on the export markets imposing the regulation.

This study contributes to the literature on the economic consequences of phytosanitary regulation on producing regions (Perrings, Mooney, and Williamson, 2010). Phytosanitary regulations are a primary means of reducing the potential risk of biological invasion from international trade and preventing ecological and economic damages that arise when invasive species become established (Olson, 2006). In the existence of such regulation, loss of apple-maggot-free status would lead to a significant increase in exporting costs and forgone exporting opportunities (Zhao, Wahl, and Marsh, 2007). Krissoff, Calvin, and Gray (1997) estimate the impact of technical barriers to trade by examining a requirement of cold treatment in Mexico and find that the impact is equivalent to a 20%–30% tariff, implying that U.S. apple producers' welfare would be considerably affected. Zhao, Wahl, and Marsh (2007) conduct a welfare analysis of the impact of the apple maggot prevention program on Washington state producers. The authors simulate different apple maggot spread rates and show that a 10% reduction in the spread rate increases producer profits by $1.52 million. The existing literature lacks analyses of how a producer might respond to a potential increase in the risk of apple maggot infestation and the effects on the producers' profitability given the phytosanitary barriers to trade. Further, the existing literature largely relies on expert opinion to parameterize population dynamics in bioeconomic models. In this study, we calibrate a model using unique apple maggot occurrence data collected from 9,832 sites across the state of Washington.

We solve our bioeconomic problem using an optimal control approach in which a producer chooses a rate of pesticide application subject to insect population dynamics. In our model, the producer faces different initial infestation levels and might be subject to a trade regulation on invasive species, depending on the location of his or her orchard (e.g., in a quarantine or pest-free area). We show that at the steady state, the phytosanitary trade regulation causing additional storage cost leads to increased rate of pesticide applications. We calibrate the model using 7 years of data (2009–2015) on yields, costs, and prices of 'Red Delicious' apples and the number of apple maggots caught in traps placed by the Washington State Department of Agriculture (WSDA). We simulate four scenarios varying by quarantine status and the existence of the phytosanitary regulations.

We find that an increased cost burden for the additional cold storage period of 40 days to export fresh apples from quarantine areas to BC and China raises the number of chemical applications, suggesting a substitution effect between pesticide application and cold storage. Results suggest that if a producer has an orchard in an apple maggot quarantine area and exports 2% of the total output to BC and China, he or she will suffer a profit loss of $185/acre (3%) compared to the profits of a producer not exporting products to the two markets. Additionally, if the unit storage cost increases by 10%, the resulting loss amounts to $1,600/acre relative to the profits made to producers not exporting products to these two markets. Further, the additional storage cost implies a delay in shipments and a decline in market prices and, consequently, profits. Our results suggest that if the proportion of 'Red Delicious' apples shipped to BC and China out of total output rises to 5%, profits may decrease by $4,881/acre (85%) compared to the case of not exporting to the two regulated export markets. This study demonstrates how a representative orchard operation's profits could be negatively affected if apple maggot establishes and spreads in the core of commercial apple production and provides the Washington State government agency with policy implications on the importance of programs minimizing the risk of apple maggot infestation in pest-free areas.

Theoretical Framework

We assume that a fruit producer faces a production environment in which apple maggot is a serious threat, which causes the majority of apple-growing areas to be quarantined. The producer's fruit can be sold either domestically or internationally, and the portion of the fruit for each destination is exogenously determined by the external entity.[3] The producer does not have the decision-making power to place their fruit either domestically or internationally and thus cannot be specialized in either market (e.g., domestic or international), regardless of the quarantine status.

The producer chooses the level of insect control to maximize the net present value of fruit production. The control variable is the rate of pesticide application u_t measured as the application per unit area at time t. The state variable is insect population g_t^i per unit area at time t for $i = \{q,\ n\}$, where i is the area in which the orchard is located, q denotes a quarantine area, and n denotes a pest-free area. The pesticide applications deter the growth of the insect population. Thus, the net growth rate of the insect stocks $\mathrm{G}\left(g_t^i\right)$ from t to $t+1$ is defined as a function of current stock level, g_t^i, net of the rate of stock eradication by pesticide applications, $\omega u_t g_t^i$, where ω is a parameter representing the mortality rate of the pesticide.

Producer revenues depend on fruit yield per unit area Y_t and prices. A producer receives a high price, p_t^h, for noninfested fruits and a low price, p_t^l, for infested fruits. Total production costs depend on the rate of pesticide applications u_t, the size of the existing pest population g_t^i, and additional storage costs S_t^i for $i = \{q,\ n\}$. Production costs rise as more pesticide is applied and insect population increases. These costs, $C(\cdot)$, are an increasing function of u_t and g_t^i (i.e., C_u and $C_g > 0\}$. The storage costs are conditioned on an exogenous phytosanitary trade regulation R imposed by importing countries on fruits shipped from quarantine areas.[4] For simplicity, we assume that the second derivatives C_{us}, C_{uu}, and C_{gg} are equal to 0.

We solve for the optimal pesticide application problem for a fruit producer with an orchard in area $i = \{q.n\}$ by maximizing the following expected profit function:

$$\max_{u_t \geq 0} \int_0^\infty e^{-\rho t} \left[p_t^h Y_t \theta\left(g_t^i\right) + p_t^l Y_t \left(1 - \theta\left(g_t^i\right)\right) - C(u_t, g_t^i, S_t^i | R) \right] dt, \tag{1}$$

where $e^{-\rho t}$ is a discount factor with discount rate ρ and $\theta(g_t^i)$ denotes the probability that the fruit is not infested by g_t^i at time t. This probability is a convex decreasing function of the insect population (i.e., $\theta_g < 0$ and $\theta_{gg} > 0$). The transversality condition is $\lim_{t\to\infty} e^{-\rho t}\lambda_t g_t^i = 0$, where λ_t is a co-state variable expressed in units of current-value net benefits associated with the insect population at time t, a shadow price for the insect population. The term $p_t^h Y_t$ measures revenues from selling noninfested fruits at the high market price, p_t^h, while $p_t^l Y_t$ measures revenues from selling infested fruits at the low market price, p_t^l. Hence, the term $p_t^h Y_t \theta\left(g_t^i\right) + p_t^l Y_t \left(1 - \theta\left(g_t^i\right)\right)$ represents a producer's expected revenues at time t from selling both noninfested and infested fruits. Storage costs are applicable only for fresh apples shipped from quarantine areas (i.e., $S_t^q | (R = 1) > 0$ and $S_t^n | (R = 0) = 0$). The profit-maximization problem is subject to the insect population equation of motion:

$$\dot{g}^i = G\left(g_t^i\right) - \omega u_t g_t^i,\ t = 0,\ 1,\ \ldots,\ T-1, \tag{2}$$

[3] The external entity, the so-called packing house, in reality offers service to the growers to market and sell their apples (Galinato et al., 2018). Washington has approximately 15 packing houses, which have both domestic and international clients and serve about 4,000 Washington apple growers. Export destination is almost uniformly distributed across packing houses.

[4] The storage problem occurs when quarantine areas affect the majority of commercial apple production. In the case of fruit shortage from pest-free areas that meet the profile requested by importers, the packing house must store the apples and wait for 40 days, which generates the extra storage cost borne by growers as presented in our model (Galinato et al., 2018).

where g_t^i is insect population in area $i = \{q, n\}$ at time t. The first term is the natural growth function, and the second term is the kill function that measures insect mortality from pesticide application (Marsh, Huffaker, and Long, 2000). The initial value of the state variable is specified as $g_0 = g^o$.

We construct the current-value Hamiltonian of a producer's problem to characterize the optimal control using Pontryagin's Maximum Principle (Clark, 1990):

$$(3) \qquad H \equiv p_t^h Y_t \theta(g_t^i) + p_t^l Y_t (1 - \theta(g_t^i)) - C(u_t, g_t^i, S_t^i | R) + \lambda_t (G(g_t^i) - \omega u_t g_t^i).$$

Ignoring the time subscripts for simplicity, the necessary conditions for a maximum are

$$(4) \qquad \frac{\partial H}{\partial u} = 0 \Leftrightarrow C_u + \lambda \omega g^i = 0,$$

$$(5) \qquad \dot{\lambda} = -\frac{\partial H}{\partial g} + \rho \lambda \Leftrightarrow \dot{\lambda} = \rho \lambda - \left(p^h - p^l\right) Y \theta_g + C_g - \lambda G_g + \lambda \omega u;$$

$$(6) \qquad \dot{g}^i = G\left(g^i\right) - \omega u_t g^i.$$

In the maximum-principle condition (equation 4), $\lambda \omega g^i$ represents the value of the marginal benefits from decreasing 1 unit of the insect population. That is, the condition describes that the marginal cost of insect control should be equal to the value of the marginal benefits from decreasing an additional unit of the insect population. The shadow price, λ_t, (interpreted as a marginal benefit of preserving the insect stock) is negative, so that there exists an interior solution. The condition ruling the behavior of the shadow price over time (equation 5) can be written with the proportionate rate of change of the shadow price on the left side: $\frac{\dot{\lambda}}{\lambda} = \rho - \frac{(p^h - p^l) Y \theta_g}{\lambda} + \frac{C_g}{\lambda} - G_g + \omega u$. The rate of change of the net benefits from controlling the insect population increases as the benefits from selling noninfested fruits increase, given that the total costs depend upon the size of the insect population ($C_g > 0$).

Our interest is in evaluating the effect of storage cost S_t^i, which is exogenously determined by phytosanitary trade regulation R, on the rate of pesticide application u_t at the steady state: du_t / dS_t^i. To do this, we first differentiate equation (4) with respect to time:

$$(7) \qquad C_{uu} \dot{u} + C_{ug} \dot{g} + \dot{\lambda} \omega g^i + \lambda \omega \dot{g}^i = 0.$$

Next, by combining equations (7) and (5) we obtain

$$(8) \qquad C_{uu} \dot{u} + C_{ug} \dot{g} + \left[\rho \lambda - \left(p^h - p^l\right) Y \theta_g + C_g - \lambda \left(G_g - \omega u\right)\right] \omega g^i + \lambda \omega \dot{g}^i = 0.$$

From equation (4), we know that $\lambda = -C_u / \omega g^i$, so equation (8) can be rewritten as

$$(9) \qquad C_{uu} \dot{u} + C_{ug} \dot{g} + \left[-\rho \frac{C_u}{\omega g^i} - (p^h - p^l) Y \theta_g + C_g + (G_g - \omega u) \frac{C_u}{\omega g^i}\right] \omega g^i - \frac{C_u \dot{g}^i}{g^i} = 0.$$

We use equations (6) and (9) for comparative statics to shed light on the relationship between S_t^i and u_t at the steady state, when all variables are unchanging with respect to time, so $\dot{u}$ and $\dot{g}$ are equal to 0. Thus, at the steady state, equations (6) and (9) can be rewritten as

$$(10) \qquad \left(C_g - p^d Y \theta_g\right) \omega g^i - (\rho + \omega u - G_g) C_u = 0, \text{ where } p^d = \left(p^h - p^l\right);$$

$$(11) \qquad G\left(g^i\right) - \omega u g^i = 0.$$

Next, we take the total derivative with respect to S_t^i for both equations and apply Cramer's rule to obtain an expression describing the comparative statics (see Appendix for derivation). Given the assumptions above, we obtain

$$(12) \qquad \frac{du_t}{dS_t^i} = -\frac{C_{sg} \omega g^i \left(G_g - \omega u\right))}{\left(\omega C_{ug} g^i - \omega C_u\right) \left(G_g - \omega u\right) + \omega g^i \left[-\left(\theta_{gg} g^i + \theta_g\right) p^d Y \omega - \left(\rho + \omega u - G_g\right) C_{ug} + G_{gg} C_u\right]}.$$

Table 1. Annual Yield and Costs in Full Production for 'Red Delicious', Average 2009–2015

	Yield[a] (40-lb box/acre)	Production Cost[a] ($/acre)	Fresh Price[b] ($/40-lb)	Processed Price[c] ($/40-lb)
7-year average	1,376	24,586	17.56	3.09

Sources: [a]Galinato and Gallardo (2016), [b]U.S. Department of Agriculture (2017a), [c]Washington State Tree Fruit Association (2017).

We also need to consider the relationship between the marginal cost of insect control and the insect stock, denoted as C_{ug}, and between the marginal cost of storage and the insect stock, denoted as C_{sg}. The cost of controlling a given number of insects is likely to increase as the insect population decreases, thus we expect that $C_{ug} < 0$. As the insect population closely approaches 0, detecting the emergence of minor insect infestations will become more difficult and expensive. Also, the cost of storing a given quantity of fruits is more likely to decrease as the insect population decreases, so $C_{sg} > 0$.

We distinguish between two cases, $G_g < \omega u_t$ and $G_g > \omega u_t$, to determine the sign of du_t/dS_t^i given these assumptions. The distinction depends on the population dynamics of the insect and the effectiveness of the pesticide. The first case ($G_g < \omega u_t$) implies that pesticides effectively deter insect population growth, while the second case ($G_g > \omega u_t$) implies otherwise. We focus on the first case to interpret the results, considering that many modern chemical pesticides used in crop production exhibit a high degree of efficacy and that apple maggot is currently under control. Therefore, the sign of du_t/dS_t^i is positive unless $G_{gg} < 0$ and the absolute values of θ_{gg} and G_{gg} are sufficiently large to offset the values of the rest of the other components with an opposite sign. Assuming that such a strict condition is hardly ever met, we thus find that a higher storage cost increases rates of pesticide application.

Empirical Model

The empirical model represents a producer of 'Red Delicious' apples, which is the largest variety (by volume) produced in Washington State. Nearly one-third of Washington State's commercial apple crop consists of 'Red Delicious', valued at approximately $621 million per year (Washington State Tree Fruit Association, 2017). It is also the most exported variety, at 50% of total apple exports, as well as one of the main varieties exported to BC and China. We calibrate the model using 'Red Delicious' data on yield (40-lb box/acre) and cost data ($/acre) in full production and using the average price between 2009 and 2015 (see Table 1).[5] Our 'Red Delicious' data and apple maggot data overlap only between 2009 and 2015. Thus, our analysis is based on this 7-year production period.

Production costs include those not affected by apple maggot infestation, namely orchard establishment, variable costs (e.g., horticultural management, harvest activities, equipment maintenance), and fixed costs such as depreciation and interest to account for the opportunity costs of the investment (Galinato and Gallardo, 2016). We assume that orchards with infestation yield a percentage of fruit damaged by apple maggot, which would only be suitable for processed juices or animal food (University of Minnesota Extension, 2017). Thus, we use processed juice prices for the damaged percentage of the annual yield and fresh 'Red Delicious' apple prices for the nondamaged percentage output.

The WSDA has identified four types of areas based on the apple maggot threat and quarantine status: (i) apple-maggot-free areas, (ii) nonquarantined but threatened areas, (iii) quarantined but nonthreatened areas, and (iv) quarantined and threatened areas. In areas designated apple-maggot-free, the insect is neither found nor established. The insect is considered established when it is expected to continue and multiply but officially being controlled. A nonquarantined but threatened area is one where the insect has been found in traps less than 0.5 miles from a commercial orchard

[5] A full production year is representative of all the remaining years after the period of orchard establishment, which typically is 4–5 years.

but is not considered established. An area quarantined but nonthreatened is where apple maggot is known to be established but has not been found in traps. Lastly, an area quarantined and threatened is where apple maggot is both found and established.

Our goal is to compare two scenarios—when an orchard is infested with apple maggot versus not—and to analyze how a producer whose orchard is infested reacts to phytosanitary export regulations. Therefore, our analyses focus on apple-maggot-free areas and quarantined and threatened areas (see Appendix Table A1). Every year, WSDA monitors apple maggot from June to September in 13 Washington counties by placing traps and reporting apple maggot findings in the traps (see Appendix Table A2). Traps are typically located in places with the greatest risk of pest introduction, particularly untreated trees such as noncommercial host trees, abandoned apple orchards, and roadside host trees. To estimate the number of apple maggots per acre per year, we use the average number of apple maggots caught in quarantine areas (90 insects) and in pest-free areas (30 insects) from 2009 to 2015 as well as orchard acreage information from the two areas considered.

Eight of the top ten export destinations for Washington apple (Canada, Mexico, United Arab Emirates, Taiwan, India, Indonesia, Vietnam, Hong Kong, Saudi Arabia, and Thailand) impose some type of restriction related to apple maggot (exceptions are Saudi Arabia and Hong Kong). Restrictions include a cold treatment consisting of storage at 1°C for 40 days, a phytosanitary certificate, etc. The last two restrictions are imposed regardless of whether apples are grown in an apple-maggot-free zone. Consequently, we assume that the additional cold storage requirement represents an additional cost only to producers with an orchard in a quarantine zone. Moreover, most destinations requiring cold treatment include restrictions on other insect pests besides apple maggot. For example, Mexico imposes restrictions for a list of pests beyond apple maggot, and requires producers in Washington, Oregon, and Idaho to comply with the "Work Plan for the Exportation of Apples from the United States to Mexico." Such plan includes among other measures, including that all apples from all producing areas (e.g., quarantined and pest-free) be held in cold storage at 1°C for 40 days (Northwest Horticultural Council, 2018). Only BC and China impose the cold storage requirement exclusively for apples grown in apple-maggot quarantine areas. Therefore, we consider the case when the orchard is located in a quarantine area and apples are to be exported to BC and China as an additional cost due to apple maggot phytosanitary regulation (Sansford, Mastro, and Reynolds, 2016).

Empirical Formulation

We specify an empirical formulation of a fruit producer's objective function in equation (1) as follows:

$$\max_{u_t \geq 0} \int_0^T e^{-\rho t} \begin{bmatrix} p_t^h Y_t (1-\gamma)^{g_t^i} + p_t^l Y_t \left(1 - (1-\gamma)^{g_t^i}\right) \\ -(c_u u_t + c_m Y_t + \ C_t + \alpha Y_t S^i | R) \end{bmatrix} dt. \tag{13}$$

The first two terms in function (13) measure the discounted revenue a producer obtains from selling 'Red Delicious' fresh and processing for juice apples, where p_t^h is the price for fresh 'Red Delicious' apples and p_t^l is the price for processing for juice apples (both expressed in \$/40-lb box). The term Y_t represents the 'Red Delicious' yield, measured in 40-lb boxes per acre at time t. The apple maggot population at period t determines damages to yield Y_t, and γ denotes the probability that apple fruits are damaged by an individual apple maggot fly. The probability that the apple fruits are not damaged by one individual maggot fly at period t is $(1-\gamma)$. The probability that the apple fruits are not damaged by apple maggot flies of population size g_t^i at period t is $(1-\gamma)^{g_t^i}$. These undamaged apples will be sold to the fresh market at price p_t^h. The revenue from selling these undamaged apples is thus $p_t^h Y_t (1-\gamma)^{g_t^i}$. The probability that apple fruits are damaged by apple maggot flies of population size g_t^i is $1-(1-\gamma)^{g_t^i}$. These fly-damaged fruits are sold for processing at price p_t^l; the revenue from selling these damaged fruits is $p_t^l Y_t\left(1-(1-\gamma)^{g_t^i}\right)$.

The third term in the objective function represents the discounted costs. Costs include pesticide application, monitoring, horticultural management, harvest, and storage. The unit costs of applying pesticides and monitoring the pest are denoted as c_u (\$/acre/application) and c_m (\$/40-lb box), respectively. The unit cost of pesticide application is the average cost of the chemicals commonly used to control apple maggot, such as Assail, Imidan, and Provado (Jay Brunner, personal communication, 2016). The unit cost of pesticide application represents the additional pesticide costs incurred due to apple maggot infestations. The costs of other chemical sprays used as a usual practice in orchard activities are included in the common production costs, C_t, presented in Table 1.[6] Note that the costs are separable, as we assume that the production input decisions are made sequentially, so that there is no substitutability in factors of production (Berndt and Christensen, 1973; Antle, 1983). The apple producers utilize their input for earlier production stages that determine yields and then make their optimal input choice of pesticide in the later stage, consistent with the so-called two-stage maximization procedure. The unit cost of monitoring is determined by the WSDA. Producers pay a monitoring cost of \$0.006/40-lb box to the state government agency for the inspection. The unit storage cost (\$/40-lb box) is denoted as S^i for $i=\{q, n\}$. For the reasons explained above, we consider export destinations BC and China as representing additional costs due to apple maggot, so the parameter α represents the percentage of total yield exported to these destinations (Washington State Tree Fruit Association, 2017). The unit storage cost is assumed to be \$0.56/40-lb box, conditioned on 85% pack-out for the 'Red Delicious' variety (Galinato and Gallardo, 2016).

A producer's chemical application decision could be affected by maximum residue limits (MRLs), which regulate maximum acceptable levels of pesticides in food and agricultural products. However, it is unlikely that a producer's choice of extra chemical applications to control apple maggots is directly constrained by MRL restrictions because a producer's concern about MRLs would be based on total pesticide use. The Northwest Horticultural Council (a nonprofit industry organization based in Yakima, Washington, that assists producers and packers in the Pacific Northwest on national and international policy issues) reports that MRL violations on Washington apples in major export markets have been rare over the past 10 years (2006–2016). In total, there have been three incidents in three destinations: India, Taiwan, and Thailand (Northwest Horticultural Council, personal communication, 2017).[7] Under this circumstance, the likelihood of changing the optimal decision of the extra chemical applications to control apple maggots is expected to be low. Thus, we consider a discussion on the role of MRL constraints in a producer's decision to be outside the scope of this study.

Apple Maggot Dynamics

Our functional form for the insect population growth is

$$g_{t+1}^i=\left[g_t^i(1-\omega)+rg_t^i(1-\omega)\left(1-\frac{g_t^i}{\kappa}\right)\right], \tag{14}$$

where r is the intrinsic growth rate, κ is the carrying capacity, and ω is the proportion of pests killed. The apple maggot population dynamics given by equation (14) have a classical Schaefer (logistic) functional form measuring the yearly growth of the population in the absence of pesticide applications. We use the growth function based on Fan, Gómez, and Atallah (2016) on optimal control strategy of spotted wing drosophila (*Drosophila suzukii*), which is in the same order (Diptera) as apple maggot (Ruiz et al., 2007). We take into consideration that pest control action changes the

[6] Other chemical sprays account for approximately 4.88% of variable production costs.

[7] In India, a small number of containers of apples were rejected (specific number unknown) in 2014. In Taiwan, five containers were rejected in 2009. In Thailand, fewer than five containers were rejected between 2014 and 2015.

Table 2. Parameter Values for the Empirical Model

Notation	Value	Unit	Description
t	7	Year	Time period
γ	0.001		Probability apple fruit damaged by one apple maggot
c_m	0.006	\$/40-lb	Unit cost of monitoring
α	2	%	Exports as percentage of total yield to BC and China
r	Uniform (0.01, 20)	Distribution	Intrinsic growth rate
κ	Uniform (100, 10000)	Distribution	Carrying capacity
ω	0.9		Proportion of pest killed
ρ	5	%	Yearly discount rate
c_u	39.98	\$/acre/application	Unit cost of applying pesticides
S^q	0.56	\$/40-lb	Unit storage cost \$11/925-lb bin[b]

Notes: [a]The unit cost of pesticide application is calculated following Jay Brunner, personal communication, 2015, under the assumption that there exists moderate pressure of codling moth.
[b]The 'Red Delicious' variety is considered an average pack-out of 85%.

state of infestation and transits to the next period. Thus, we incorporate the proportion of pests killed, ω, into equation (14) as a parameter.

The problem of applying population dynamics as defined in equation (14) is that the true apple maggot population is unknown. In general, insect observation data collected from the traps strategically located in the field (or close by) provide only noisy information about true population dynamics rather than actual population size (Fan, Gómez, and Atallah, 2016). Therefore, we assume that trapping efficiency is uniformly distributed between 0.1% and 1%. This assumption is based on Lance and Gates (1994), who determined the probability of capturing Mediterranean fruit flies in standard trapping arrays (using 10 traps per square mile) and found that the percentage of flies recaptured is approximately 0.6% overall. The number of detections is determined through a binomial sampling—being captured or escaping—from the population, and the maximum number of the detections is set to be less than the population. We estimate the insect population using the variational inference method using Python.[8] Lastly, we assume that the intrinsic growth rate, r, and carrying capacity, κ, follow a uniform distribution, which is the most noninformative distribution. It is usually chosen as priors when scientists do not know much about the parameters to be estimated (Fan, Gómez, and Atallah, 2016).[9] Table 2 lists the parameter values used to calibrate the model. Using the estimated apple maggot population size and the parameter values, we calculate the probability that fruit is damaged by the total number of apple maggots. Similar to Fan, Gómez, and Atallah, we use = 0.001, implying that the probability the fruit is noninfested is 0.999. The probability that the fruit remains noninfested from the population size of apple maggot g_t^i is $(0.999)^{g_t^i}$, denoted as $\theta\left(g_t^i\right)$ in equation (1), so the probability that the fruit is damaged by the population g_t^i is $1-(0.999)^{g_t^i}$, denoted as $\left(1-\theta\left(g_t^i\right)\right)$ in equation (1). The probability is calculated using the estimated population size of apple maggot with the data on apple maggot findings, presented in Table A2.

[8] Variational inference turns the problem of inference, which often requires expensive sampling from an intractable posterior distribution, into an optimization problem that can be efficiently solved often using an off-the-shelf, gradient-based optimization algorithm. To do so, variational inference introduces a parametrized (approximate) posterior distribution over the latent variables given each observation and maximizes the variational lower bound to the marginal log-probability of observations. We can use the estimated posterior distributions as a proxy of the true posterior distributions and use them to compute a quantity of interest. The major advantage of variational inference is its computational efficiency. It is also considered beneficial over more traditional sampling-based inference because variational inference exhibits less stochastic behaviors (Ranganath, Gerrish, and Blei, 2014).

[9] Fan, Gómez, and Atallah (2016) use Bayesian rules to estimate parameters and choose uniform distributions as priors for r and κ. This is because spotted wing drosophila is a relatively new invasive species and scientists do not have much information about it.

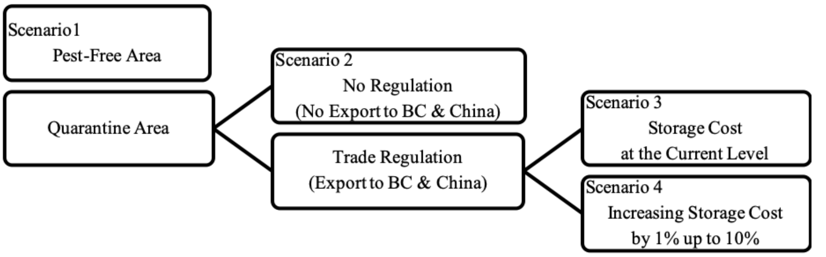

Figure 1. Flow of Scenarios

Scenarios, Simulation, and Results

To investigate the change in a producer's profits under different levels of pest infestation and existence of phytosanitary trade regulations, we separately estimate a producer's profits considering pest-free and quarantine status. Next, we estimate the economic impact of the phytosanitary regulation applied to fresh apples shipped from quarantine areas to BC and China. Finally, we show how the producer's optimal pesticide applications and profits change as the cost burden for the cold treatment to meet the phytosanitary trade regulation increases.

Figure 1 illustrates the four scenarios examined. The first scenario represents an orchard located in a pest-free area, so the phytosanitary trade regulation does not apply. The second scenario describes a producer's orchard located in a quarantine area, but the producer does not export apple fruits to BC and China, so the apple maggot trade regulation does not apply. The second scenario is our baseline, "no regulation" scenario. Under the third scenario, a producer would have an orchard in a quarantine area, export 2% of the orchards total yield to BC and China, and face the current level of the cost burden from cold treatment ($11/40-lb box/40 days at 1°C). Under the last scenario, a producer would have an orchard in a quarantine area and increase exports to BC and China, leading to a rise in costs from cold treatment storage of between 1% and 10%.

Table 3 presents the simulation results of the four scenarios. In the pest-free scenario (scenario 1), the 7-year estimated profits for a producer with an orchard in a pest-free area are −$5,339/acre.[10] This profit differs from the production costs outlined in Galinato and Gallardo (2016), who estimated 7-year profits of −$3,792/acre.[11] The main reason for the difference in profits is that the authors did not consider additional spray costs due to the potential apple maggot infestation, leading to unmarketable fresh fruit. In contrast, we assume here that the chemical spray costs to control apple maggots would change as a producer adjusts spray rates according to the variation of the insect population. Galinato and Gallardo (2016) assume that the chemical costs to control for insects are fixed at $199.91/acre. Our results indicate that the optimal annual spray cost amounts to an average of $316/acre, reflecting variations in spray application strategies due to insect population dynamics even in a pest-free scenario.[12]

For scenario 2, the estimated 7-year profits for a 'Red Delicious' apple orchard operation located in a quarantine area that does not export to BC and China are −$5,737/acre. When an apple maggot infestation is introduced to an orchard, profits are reduced by $398/acre (equivalent to 7%) compared to the pest-free scenario. Considering that the average size of a Washington farm is between 350 and 400 acres (U.S. Department of Agriculture, 2012), the economic loss for an orchard operation could range from $139,300 to $159,200 for a 7-year operation.

[10] The profits appear to be negative because the price in the 2014–2015 marketing year was particularly low (less than $14/40-lb box), lowering the average price used to estimate the 7-year profits. Average prices in remaining marketing years have ranged from $18/40-lb box to $19/40-lb box.

[11] The estimated 7-year profits in Galinato and Gallardo (2016) are $1,242/acre (using a price of $18.16/40-lb box). The re-estimated profits in their study should decrease from $1,242 to −$3,792 after using a lower average price ($17.56/40-lb box).

[12] $315.84 = 7.9 \times 39.98$ (= unit spray cost). Recall that apple maggot was found in pest-free areas but not considered as threatened or quarantined.

Table 3. Result of Empirical Model, Profits and Pesticide Applications for 7 Years

Area	Pest-Free	Baseline	Quarantine										
Scenario	**1**	**2**	**3**	**4-1**	**4-2**	**4-3**	**4-4**	**4-5**	**4-6**	**4-7**	**4-8**	**4-9**	**4-10**
Storage cost ($)	0	0	0.56	0.566	0.571	0.5768	0.582	0.588	0.594	0.599	0.605	0.61	0.616
Increasing rate of storage cost (%)			0%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
7-year profits ($/acre)	-5,339	-5,737	-5,922	-6,616	-6,885	-6,962	-6,942	-7,089	-7,011	-7,021	-7,339	-7,047	-7,337
Optimal pesticide applications (sprays/year)	10.99	7.9	9.34	11.66	12.75	12.79	12.57	13.6	12.86	13.89	14.51	13.5	14.27

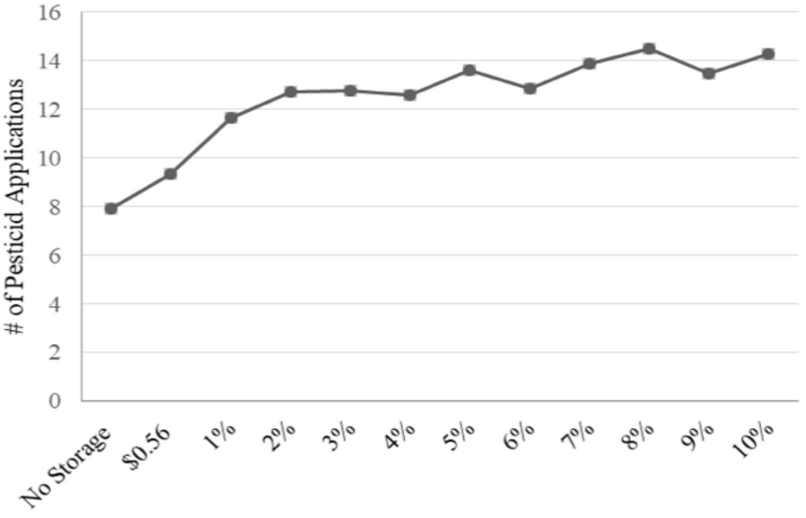

Figure 2. Pesticide Application Rate and Storage Cost

Notes: Each data point is an average value of the number of pesticide applications over 7 years.

For scenario 3, the estimated 7-year profits are $-$5,922/acre. The trade regulation of invasive species that requires the cold storage period for fresh apples shipped from quarantine areas causes additional economic losses of $185/acre (equivalent to 3%) compared to those estimated in the baseline scenario. This loss amounts to approximately $64,750–$74,000 more than in the baseline scenario for a 7-year operation on an average-size farm in Washington State. The number of necessary sprays increases from eight to nine per year.

For scenario 4, when the producer faces increasing storage costs, if the unit storage cost increases by 10%, estimated profits decrease to $-$7,337/acre. The additional economic loss amounts to $1,600/acre (equivalent to 28%) compared to the profit estimated in the baseline scenario. The empirical relationship between the rate of the pesticide application and the storage cost is consistent with our theoretical result (equation 12). We examine the relationship between the two variables by increasing the unit storage cost by 1% up to 10%. We find that the larger the cost burden for cold treatment, the higher the number of sprays (Figure 2).

Effect of Delayed Shipment due to Storage Period

In addition to storage costs, the mandatory cold storage treatment of fresh apples also decreases producer profits because of the 40-day delay in shipping apples to the destination market. For example, if 'Red Delicious' apples harvested in September in quarantine areas must be shipped in October due to the 40-day storage requirement, the producer would receive the October market price. The market price in October is lower than in September since price competition with other varieties generally gets more intense in the later season as the bulk of apple varieties become available on the market. To examine the effect of delayed shipment due to the required storage period, we use the supply elasticity to calculate expected market prices and profits accordingly. The estimated supply elasticity for 'Red Delicious' is -1.03 (Galinato, Gallardo, and Granatstein, 2017).[13]

We consider the case in which the supply change is only attributed to the delay in shipments of fresh apples produced in quarantine areas to two export markets: BC and China. By doing so, we can measure how the market price of 'Red Delicious' changes as its export quantity to those two export markets increases. The market price is expected to decrease as the share of yield shipped to BC and China increases. Assuming that the supply elasticity is constant, we measure the fall in market prices

[13] Authors' calculations; available upon request.

Table 4. Effect of the Delayed Shipment on Prices and Profits

	Current	Projection		
Export to BC and China (% of total yield)	2%	3%	4%	5%
Estimated price ($/40-lb box)	17.56	17.38	17.2	17.02
7-year profits ($/acre)	-5,922	-8,986	-9,289	-10,618

resulting from an increase in shipments to these two markets from 2% (the current level) to 5% of the total output. Table 4 shows that if the share of the 'Red Delicious' apples shipped to BC and China out of total output rises to 5%, profits will decrease to −$10,618/acre, a difference of $4,881/acre, equivalent to a 85% decline in profits compared to the baseline scenario at −$5,737/acre in which the apple orchard operation is located in a quarantine area but does not export to BC and China.

Summary and Conclusions

This study examines the effect of trade regulation of invasive species on producers' optimal control and evaluates its economic consequences. We theoretically model how a producer adjusts his or her pesticide application when faced with different circumstances, infestation intensities, and the existence of phytosanitary trade regulation. Our model predicts that the higher cost burden associated with complying with the regulation increases the rate of pesticide applications.

Using 7 years of data on 'Red Delicious' and the number of trapped apple maggots in Washington, we simulate the model under four scenarios varying by quarantine status (pest-free, quarantine) and the existence of the phytosanitary regulations requiring additional cold storage. Our empirical simulation results are consistent with our theoretical results in that an increasing cost burden for the cold treatment, required to export fresh apples from quarantine areas to BC and China, raises the number of chemical applications, suggesting a substitution effect between pesticide application and cold storage. If a producer has an orchard within quarantine areas and exports 2% of their total yield to BC and China, he or she will encounter a profit loss of approximately $185/acre compared to producers not exporting to these two markets. For a producer with an average-sized farm (350–400 acres), the loss amounts to approximately $64,750–$74,400. Further, we account for the possibility that late shipment due to the phytosanitary regulation could cause the market price of fresh apples harvested relatively early to fall. We found that if the share of the output shipped to the two markets rises to 5%, profits decrease by $4,881/acre (85%) compared to the baseline case of not exporting to the two markets.

Considering the increasing dependency of the industry on export markets, findings in this study could be useful in motivating policy to prevent apple maggot expansion in Washington State. This study demonstrates how a representative orchard operation's profits could be negatively affected if apple maggot spreads and establishes in the core of commercial apple production in Washington State. Given the importance of the apple industry to the state's economy, these findings suggest that the risk of apple maggot infestation should be kept at minimum levels by preventing any practice that would increase this risk. It also shows the economic impact of the phytosanitary regulations. In a scenario where the U.S. apple industry is becoming more dependent on export markets, negotiating phytosanitary regulations is key to guaranteeing the apple operations' economic profitability.

[First submitted May 2018; accepted for publication December 2018.]

References

Ali Niazee, M. T., and R. L. Penrose. “Apple Maggot in Oregon: A Possible New Threat to the Northwest Apple Industry.” *Bulletin of the Entomological Society of America* 27(1981):245–246. doi: 10.1093/besa/27.4.245.

Antle, J. M. “Sequential Decision Making in Production Models.” *American Journal of Agricultural Economics* 65(1983):282–290. doi: 10.2307/1240874.

Berndt, E. R., and L. R. Christensen. “The Internal Structure of Functional Relationships: Separability, Substitution, and Aggregation.” *Review of Economic Studies* 40(1973):403–410. doi: 10.2307/2296459.

Boller, E. F., and R. J. Prokopy. “Bionomics and Management of Rhagoletis.” *Annual Review of Entomology* 21(1976):223–246. doi: 10.1146/annurev.en.21.010176.001255.

Bruinsma, J. *World Agriculture: Towards 2015/2030: An FAO Study*. London, UK: Routledge, 2017, ebook edition ed.

Calvin, L., and B. Krissoff. “Technical Barriers to Trade: A Case Study of Phytosanitary Barriers and U.S.–Japanese Apple Trade.” *Journal of Agricultural and Resource Economics* 23(1998):351.

Calvin, L., B. Krissoff, and W. Foster. “Measuring the Costs and Trade Effects of Phytosanitary Protocols: A U.S.–Japanese Apple Example.” *Review of Agricultural Economics* 30(2008):120–135. doi: 10.1111/j.1467-9353.2007.00395.x.

Clark, C. W. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. New York, NY: Wiley-Interscience, 1990, 2nd ed.

Corn, M. L., and R. Johnson. “Invasive Species: Major Laws and the Role of Selected Federal Agencies.” CRS Report R43258, Congressional Research Service, Washington, DC, 2013.

Dean, R. W., and P. J. Chapman. “Bionomics of the Apple Maggot in Eastern New York.” *Search* 10(1973):1–64.

Disdier, A.-C., L. Fontagné, and M. Mimouni. “The Impact of Regulations on Agricultural Trade: Evidence from the SPS and TBT Agreements.” *American Journal of Agricultural Economics* 90(2008):336–350. doi: 10.1111/j.1467-8276.2007.01127.x.

Fan, X., M. Gómez, and S. Atallah. “Optimal Monitoring and Controlling of Invasive Species: The Case of Spotted Wing Drosophila in the United States.” 2016. Paper presented at the annual meeting of the Agricultural and Applied Economics Association, Boston, Massachusetts, July 31-August 2.

Galinato, S., and R. K. Gallardo. “2014 Cost Estimates of Establishing, Producing, and Packing Red Delicious Apples in Washington.” Extension Fact Sheet TB07E, Washington State University, School of Economic Sciences, Tree Fruit Research and Extension Center, Wenatchee, WA, 2016.

Galinato, S. P., R. K. Gallardo, and D. M. Granatstein. “Economic Impact of Apple Maggot Infestation in Washington.” 2017. Final Report to the Washington Tree Fruit Research Commission.

Galinato, S. P., R. K. Gallardo, D. M. Granatstein, and M. Willett. “Economic Impact of a Potential Expansion of Pest Infestation: Apple Maggot in Washington State.” *HortTechnology* 28(2018):651–659. doi: 10.21273/HORTTECH04141-18.

Glass, E. H., and S. E. Lienk. “Apple Insect and Mite Populations Developing After Discontinuance of Insecticides: 10-Year Record1.” *Journal of Economic Entomology* 64(1971):23–26. doi: 10.1093/jee/64.1.23.

Gray, R. S., D. A. Sumner, J. M. Alston, and H. Brunke. “Economic Impacts of Mandated Grading and Testing to Avoid a Negative Food Safety Event: Ex ante Analysis of the Federal Marketing Order for Pistachios.” 2004. Paper presented at the annual meeting of the American Agricultural Economics Association, Denver, Colorado, August 1-4.

Howitt, A. “Common Tree Fruit Pests.” Publication NCR063, Michigan State University, Ann Arbor, MI, 1993.

Klaus, M. W. *2015 Apple Maggot Survey Summary*. Olympia, WA: Washington State Department of Agriculture, 2015a.

———. *Apple Maggot Working Group Presentation*. Olympia, WA: Washington State Department of Agriculture, 2015b.

Krissoff, B., L. Calvin, and D. Gray. “Barriers to Trade in Global Apple Markets.” Fruit and Tree Nut Situation and Outlook FTS-280, U. S. Department of Agriculture, Economic Research Service, Washington, DC, 1997.

Lance, D. R., and D. B. Gates. “Sensitivity of Detection Trapping Systems for Mediterranean Fruit Flies (Diptera: Tephritidae) in Southern California.” *Journal of Economic Entomology* 87(1994):1377–1383. doi: 10.1093/jee/87.6.1377.

Levine, J. M., and C. M. D’Antonio. “Forecasting Biological Invasions with Increasing International Trade.” *Conservation Biology* 17(2003):322–326. doi: 10.1046/j.1523-1739.2003.02038.x.

Liu, L., and C. Yue. “Non-Tariff Barriers to Trade Caused by SPS Measures and Customs Procedures with Product Quality Changes.” *Journal of Agricultural and Resource Economics* 34(2009):196–212.

Marsh, T. L., R. G. Huffaker, and G. E. Long. “Optimal Control of Vector-Virus-Plant Interactions: The Case of Potato Leafroll Virus Net Necrosis.” *American Journal of Agricultural Economics* 82(2000):556–569. doi: 10.1111/0002-9092.00046.

Northwest Horticultural Council. “Export Manual: Individual Countries.” 2018. Available online at http://nwhort.org/exportmanual/countries-toc/ [Accessed August 15, 2018.].

Olson, L. J. “The Economics of Terrestrial Invasive Species: A Review of the Literature.” *Agricultural and Resource Economics Review* 35(2006):178–194. doi: 10.1017/S1068280500010145.

Perrings, C., H. Mooney, and M. Williamson. *Bioinvasions and Globalization: Ecology, Economics, Management, and Policy*. Oxford, UK: Oxford University Press, 2010.

Ranganath, R., S. Gerrish, and D. M. Blei. “Black Box Variational Inference.” *Proceedings of the Seventeenth International Conference on Artificial Intelligence and Statistics* 33(2014):814–822.

Ruiz, M. F., A. Milano, M. Salvemini, J. M. Eirín-López, A. L. P. Perondini, D. Selivon, C. Polito, G. Saccone, and L. Sánchez. “The Gene Transformer of Anastrepha Fruit Flies (Diptera, Tephritidae) and Its Evolution in Insects.” *PLoS ONE* 2(2007):e1239. doi: 10.1371/journal.pone.0001239.

Sansford, C. E., V. Mastro, and J. R. Reynolds. *Pest Risk Analysis (PRA) for Apple Maggot (Rhagoletis pomonella) Moving on Municipal Green Waste into the Pest-Free Area (PFA) of the State of Washington USA*. Olympia, WA: Washington State Department of Agriculture, 2016.

United Nations. “UN Comtrade Database.” 2016. Available online at https://comtrade.un.org/.

University of Minnesota Extension. *Apple Maggot*. Minneapolis, MN: University of Minnesota Extension, 2017. Available online at https://www.extension.umn.edu/garden/yard-garden/fruit/apple-pest-management/maggot/.

U.S. Department of Agriculture. *The Pride of Washington State*. Olympia, WA: U.S. Department of Agriculture, National Agricultural Statistics Service, Washington Field Office, 2012. Available online at https://www.nass.usda.gov/Statistics_by_State/Washington/Publications/wabro.pdf.

———. *Fruit and Tree Nuts Yearbook 2016*. Washington, DC: U.S. Department of Agriculture, Economic Research Service, 2017a.

———. *Invasive Species: Laws and Regulations - International: Global Conventions*. Washington, DC: U.S. Department of Agriculture, National Agricultural Library, 2017b. Available online at https://web.archive.org/web/20170406235010/https://www.invasivespeciesinfo.gov/laws/intlglobalconv.shtml.

———. *Noncitrus Fruits and Nuts 2016 Summary*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service, 2017c.

Washington State Department of Agriculture. *Apple Maggot Survey Summary Report*. Yakima, WA: Washington State Department of Agriculture, 2005.

———. *Apple Maggot Survey Summary Report*. Yakima, WA: Washington State Department of Agriculture, 2008.

———. *Apple Maggot Survey Summary Report*. Yakima, WA: Washington State Department of Agriculture, 2013.

———. *Apple Maggot Survey Summary Report*. Yakima, WA: Washington State Department of Agriculture, 2015.

Washington State Tree Fruit Association. *Annual Crop Summary: 2015-2016 Marketing Season*. Yakima, WA: Washington State Tree Fruit Association, 2017. Available online at https://wstfa.org/wstfa-assets/uploads/2016-17-Annual-Growers-Review.pdf.

Yue, C., J. Beghin, and H. H. Jensen. "Tariff Equivalent of Technical Barriers to Trade with Imperfect Substitution and Trade Costs." *American Journal of Agricultural Economics* 88(2006):947–960. doi: 10.1111/j.1467-8276.2006.00908.x.

Zhao, Z., T. Wahl, and T. Marsh. "Economic Effects of Mitigating Apple Maggot Spread." *Canadian Journal of Agricultural Economics* 55(2007):499–514. doi: 10.1111/j.1744-7976.2007.00105.x.

Appendix: Total Derivation and Cramer's Rule for Comparative Statistics

Taking the total derivative with respect to S_t^i for each of equations (10) and (11) yields

$$\begin{aligned}(\text{A1})\qquad & \omega C_{gu}\frac{du}{ds}g^i + \omega C_{gg}\frac{dg^i}{ds}g^i + \omega C_{gs}g^i - p^d Y\omega\theta_{gg}\frac{dg^i}{ds}g^i - p^d Y\omega\theta_g\frac{dg^i}{ds} \\ & -\rho C_{uu}\frac{du}{ds} - \rho C_{ug}\frac{dg^i}{ds} - \rho C_{us} - \omega C_u\frac{du}{ds} - \omega u C_{uu}\frac{du}{ds} - \omega u C_{ug}\frac{dg^i}{ds} \\ & -\omega u C_{us} + G_{gg}\frac{dg^i}{ds}C_u + G_g C_{uu}\frac{du}{ds} + G_g C_{ug}\frac{dg^i}{ds} + G_g C_{us} = 0.\end{aligned}$$

$$(\text{A2})\qquad G_g\frac{dg^i}{ds} - \omega g^i\frac{du}{ds} - \omega u\frac{dg^i}{ds} = 0.$$

The matrix format is

$$\begin{bmatrix}\omega C_{gg}g^i - p^d Y\omega\theta_{gg}g^i - p^d Y\omega\theta_g - \rho C_{ug} - \omega u C_{ug} + G_{gg}C_u + G_g C_{ug} & \omega C_{gu}g^i - \rho C_{uu} - \omega C_u - \omega u C_{uu} + G_g C_{uu} \\ G_g - \omega u & -\omega g^i\end{bmatrix}\begin{bmatrix}\frac{dg^i}{ds} \\ \frac{du}{ds}\end{bmatrix} =$$
$$\begin{bmatrix}-\omega C_{gs}g^i + \rho C_{us} - G_g C_{us} + \omega u C_{us} \\ 0\end{bmatrix}.$$

By Cramer's rule, we see that

$$(\text{A3})\qquad \frac{du_t}{dS_t^i} = -\frac{\begin{vmatrix}\omega_{C_{gg}}g^i - p^d Y\omega\theta_{gg}g^i - p^d Y\omega\theta_g - \rho C_{ug} - \omega u C_{ug} + G_{gg}C_u + G_g C_{ug} & -\omega C_{gs}g^i + \rho C_{us} - G_g C_{us} + \omega u C_{us} \\ G_{gg} - \omega u & 0\end{vmatrix}}{\begin{vmatrix}\omega C_{gg}g^i - p^d Y\omega\theta_{gg}g^i - p^d Y\omega\theta_g - \rho C_{ug} - \omega u C_{ug} + G_{gg}C_u + G_g C_{ug} & \omega C_{gu}g^i - \rho C_{uu} - \omega C_u - \omega u C_{uu} + G_g C_{uu} \\ G_g - \omega u & -\omega g^i\end{vmatrix}}.$$

The comparative statics between S_t^i and u_t at the steady state is driven as follows:

$$(\text{A4})\qquad \frac{du_t}{dS_t^i} = -\frac{\left[C_{gs}\omega g^i - (\rho + \omega u - G_g)C_{us}\right](G_g - \omega u)}{\left[\omega C_{gu}g^i - (\rho + \omega u - G_g)C_{uu} - \omega C_u\right](G_g - \omega u) + \omega g^i\left[\omega C_{gg}g^i - (\theta_{gg}g^i + \theta_g)p^d Y\omega - (\rho + \omega u - G_g)C_{ug} + G_{gg}C_u\right]}.$$

Table A1. Apple Orchard Acreage by Threat and Quarantine Status due to Apple Maggot

		Conventional Apple Orchards	
Threat Status of Orchards	**Quarantine Status**	**Acres**	**% of Total**
AM threatened	Quarantine	1,351	0.83%
AM threatened	Nonquarantine	184	0.11%
Nonthreatened	Quarantine	23,224	14.21%
Nonthreatened	Nonquarantine	138,683	84.85%
Total		163,442	100.00%

Source: WSDA Natural Resources Assessment Section WSDA Pest Program (personal communication, 2016).

Table A2. Insect-Vector Stocks per Unit Area

Year	Total	Quarantine	Pest-Free
2015	283	220	63
2014	131	95	36
2013	78	25	53
2012	67	51	16
2011	58	35	23
2010	103	91	12
2009	123	115	8
2008	300	284	16
2007	287	266	21
2006	232	226	6
2005	872	845	27
2004	171	136	35
2003	60	60	0

Source: Washington State Department of Agriculture (2005, 2008, 2013, 2015) and unpublished data on insect stocks from the Washington State Department of Agriculture.