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The Economic Impacts and Management of Spotted Wing Drosophila (*Drosophila Suzukii*): The Case of Wild Blueberries in Maine

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Abstract

Drosophila suzukii (Matsumura), or spotted wing drosophila, has become a major pest concern for berry growers in the United States. In this study, we evaluated the economic impacts of *D. suzukii* on the Maine wild blueberry industry from two perspectives. The first analysis estimated the state-level economic impacts of *D. suzukii* on the wild blueberry industry in Maine in the absence of control. We found that *D. suzukii* could result in drastic revenue losses to the industry, which could be over $6.8 million under the worst-case scenario (assuming a 30% yield reduction). In the second analysis, we used Monte Carlo simulation to compare the expected revenues under different management strategies for a typical wild blueberry farm in Maine. The analysis focused on a decision-making week during the harvesting season, which the grower can choose in between three control strategies: no-control, early harvest, or insecticide application. The results suggested that insecticide applications are not economically optimal in most low infestation risk scenarios. Furthermore, although the early harvest strategy is one of the strategies to avoid *D. suzukii* infestations for wild blueberry production in Maine, the tradeoff is the revenue loss from the unripe crop. Using the simulation results, we summarized optimal harvest timing regarding the fruit maturity level under different *D. suzukii* infestation risk scenarios, which can minimize the revenue loss from adopting the early harvest management strategy.

Key words: pest management, crop loss, blueberry infestation, action threshold, *Vaccinium angustifolium*

Drosophila suzukii (Matsumura), also known as spotted wing drosophila (SWD), is an invasive pest of soft-skinned fruits that originated from East Asia. In the United States, *D. suzukii* was first detected in Hawaii in 1980 and then in California in 2008 and has now expanded its invaded range to much of the continental United States (Bolda et al. 2010, Walsh et al. 2011). Unlike most other *Drosophila* species, the female *D. suzukii* has a serrated ovipositor that allows it to lay eggs in ripening fruits (Walsh et al. 2011). Once the fruits are infested, the internal larval feeding causes direct damage to the fruit, while oviposition also exposes fruit to secondary bacteria and yeast pathogens (Cini et al. 2012, Asplen et al. 2015, Ioriatti et al. 2015). Studies have shown significant negative economic impacts from *D. suzukii* in the United States (Bolda et al. 2010, Goodhue et al. 2011, Farnsworth et al. 2017). Most of the previous economic research focuses on the West Coast berry industry. There exists a gap in the literature on understanding the economic impacts of *D. suzukii* on the East Coast's blueberry industry.

In this study, we evaluated the economic impacts of *D. suzukii* on wild (low-bush) blueberry production in Maine. According to the production statistics published by the U.S. Department of Agriculture (2019a), Maine plays an important role in the U.S. blueberry production. Maine was the third largest state in domestic blueberry production in terms of volume during 2017 after Oregon and Michigan (U.S. Department of Agriculture 2019a), and the state produced over 30,000 metric tons of wild blueberries during 2017, which represented about 12% of total domestic blueberry production including cultivated (high-bush) blueberries (U.S. Department of Agriculture 2019a).

Drosophila suzukii was first detected in Maine blueberry fields in 2012 (Drummond et al. 2018) and has become one of the major pest problems for wild blueberry growers in the state (Drummond et al. 2019). Facing the risk of *D. suzukii* infestation, most Maine wild blueberry growers have been using SWD-targeted control tactics to avoid infestation, mainly increased insecticide applications (Drummond et al. 2019, Yarborough et al. 2019). Some growers, however, have been employing cultural controls for *D. suzukii*, such as harvesting earlier in the season (Drummond et al. 2019). *Drosophila suzukii* is a mid-to-late season pest for Maine growers given the northern geographic location of production (Drummond et al. 2018). While early harvest may circumvent the higher pest pressure later in the production season, one of the tradeoffs is that growers may experience yield losses due to immature green fruit left in the field or discarded at the processing line (Drummond et al. 2019). As an alternative, when the field is closed to full fruit maturity, growers can apply insecticides to lower the risk of *D. suzukii* infestation and wait until the fruit reaches full maturity prior to harvest. However, the associated costs from applying insecticide may be larger than the yield loss accrued from early harvest.

We addressed the economic impacts of *D. suzukii* on Maine wild blueberry production from two perspectives in this study. We first evaluated the economic impacts of *D. suzukii* at the aggregated state-level to understand the economic impacts of *D. suzukii* on the Maine wild blueberry industry. Then, we conducted a farm-level analysis to identify the economically optimal *D. suzukii* control strategies at different fruit ripeness levels for a typical wild blueberry farm in Maine. In the farm-level analysis, we included different perceived risk levels of *D. suzukii* infestation, which assumed that growers predicted their risks of infestation from actively monitoring their fields with traps. We also included three levels of blueberry market price to evaluate how the optimal management strategy may be affected by market conditions. The farm-level analysis considered economic tradeoffs between the strategy of no-control (waiting to harvest), early harvest, and applying insecticide at the decision-making week, which can provide valuable information to stakeholders to control *D. suzukii* infestations sustainably.

Materials and Methods

State-Level Economic Impacts of *D. suzukii* on the Wild Blueberry Industry in Maine

To understand the economic impact of *D. suzukii* at the state-level, we estimated the changes in total revenue based on the current production parameters and the hypothetical changes in yield and insecticide usage induced by preventing the *D. suzukii* infestation. The production system of wild blueberry was segregated into organic and conventional farming systems, where the conventional system was further categorized into low-, medium-, and high-input systems (see Chen et al. (2017) for a detailed description). For each of the four farming systems, the comparison baseline was the total revenue calculated in equation 1 for the 2017–2018 production season.

$$\begin{aligned}&\text{Total cost of additional insecticide application(s)}\\&\quad = \text{Harvested hectares} \times \text{cost per application}\\&\qquad \times \text{Number of additional application(s)}\end{aligned} \quad (1)$$

The total harvested hectares and market prices for each farming system were averaged using the 2017 estimates from U.S. Department of Agriculture (2019a). The average market farm-gate price of conventional processed frozen wild blueberries was $0.57/kg, while for organic wild blueberries which were mostly sold at the fresh market, the farm-gate price was substantially higher at $13.23/kg. The percentage breakdowns of the total production hectares for each farming system were estimated as low-input at 20%, medium-input at 33%, high-input at 45%, and organic at 2% (Yarborough, pers. comm.). The average yields per hectare for each production system were based on Asare et al. (2017).

Given that *D. suzukii* has become a persistent pest problem for domestic berry growers since 2012, growers have mostly relied on the increased frequency of insecticide applications to protect their crops from *D. suzukii* infestation (Asplen et al. 2015, Drummond et al. 2018). Although crop loss has been controlled at low levels, *D. suzukii*-targeted insecticide applications have caused a significant increase in production costs (De Ros et al. 2015, Del Fava et al. 2017, Farnsworth et al. 2017). According to Drummond et al. (2019), fruit infestation rates due to *D. suzukii* in Maine wild blueberry have been relatively low, ranging from 0 to 5% in recent years. However, during the first year of the introduction of *D. suzukii* into Maine (i.e., 2012), some wild blueberry processors reported 25–30% crop loss due to *D. suzukii* (Drummond et al. 2018). Previous studies in other berry production regions also suggested 20% or higher yield losses if *D. suzukii* was left uncontrolled (Bolda et al. 2010, Goodhue et al. 2011, Walsh et al. 2011). Therefore, we calculated the aggregated state-level revenue losses under three hypothetical yield reductions, 5, 10, and 30%, from the baseline revenue.

In addition to the hypothetical yield reduction, we calculated the total additional cost from *D. suzukii*-targeted insecticide applications ranging from one to three times per season (equation 2). The average cost for insecticide application was estimated at $75.9/ha ($30.7/acre; Yarborough and D'Appollonio 2017, Drummond et al. 2018, Esau 2019). We also reported the percentage of spraying cost to the total revenue for each conventional farming system using the baseline total revenue specified in equation 1. This analysis was conducted only for the conventional system but not for organic production because insecticides are used less frequently in organic production (Drummond et al. 2019).

$$\begin{aligned}&\text{Total cost of additional insecticide application(s)}\\&\quad = \text{Harvested hectares} \times \text{cost per application}\\&\qquad \times \text{Number of additional application(s)}\end{aligned} \quad (2)$$

Farm-Level Economic Analysis

In the farm-level economic analysis, our objective was to understand the economic tradeoffs among *D. suzukii* control tactics. We compared the expected economic outcomes of three management strategies in this analysis: 1) The no-control (baseline) strategy, 2) the early harvest strategy, and 3) the insecticide application strategy. The analysis focused on a given week when the crop was close to full maturity (starting at 60% ripeness and beyond), and in which a grower must decide whether to apply insecticide, harvest right away, or wait for the following week to harvest (no-control). We listed the grower's action at the given week and the following week for each management strategy in Table 1. We assumed the grower's management practice in the prior weeks was independent of the strategy chosen at this given week.

We numerically compared and ranked the expected revenue of each management strategy on different stages of the production cycle based on the level of fruit ripeness. Equations 3–6 were used to calculate the expected revenue for each strategy. First, equation

Table 1. *Drosophila suzukii* management strategies in the farm-level economic analysis

Strategy	Action at the given week	Action at the following week
1. No-control (baseline)	(No action)	Harvest
2. Early harvest	Harvest	(No action)
3. Insecticide application	Apply insecticide	Harvest

3 was retrieved from Drummond et al. (2019), which estimates the percentage of ripe fruit as a function of Julian Date. Based on a given ripeness percentage of week t, we used the result of equation 3 to approximate the ripeness of the following week at $t + 1$ (i.e., 7 d after). The yield at week t ($yield_t$) was specified in equation 4, which was calculated as the baseline yield at full maturity ($base\_yield$) times the percentage of ripeness at week t ($ripe_t$).

$$\% \text{ of ripe fruit} \equiv ripe_t = \frac{100}{1 + \exp(30.903 - 0.159 \times JulianDate(t))} \quad (3)$$

$$yield_t = base\_yield \times ripe_t \quad (4)$$

One of the key elements of the farm-level analysis was to incorporate the different risk levels of *D. suzukii* infestation for the comparison. To quantitatively compare the economic outcomes under different *D. suzukii* infestation risk levels, we assumed that growers actively monitor *D. suzukii* using traps throughout the production season. We used the estimated probabilities of future fruit infestation from Drummond et al. (2019). Based on the cumulative *D. suzukii* male captures in a given week, Drummond et al. (2019) collected field data to statistically infer the probability of having infested fruit the following week. We included three risk levels on future infestation: low, medium, and high risk, assuming the three risk levels correspond to an average of 2, 7, and 16 cumulative male *D. suzukii* per trap capture at a given week (Drummond et al. 2019). The three risk levels – low, medium, and high – for future infestation indicates the infestation probabilities at the following week to be at 5, 25, and 50%, respectively (Drummond et al. 2018, 2019). We ran three sets of revenue scenarios, each using one of the three risk levels of the infestation probabilities, inf_prob (equation 5).

$$Rev\_risk_t = \begin{cases} yield_t \times (1 - inf\_loss) \times p, & \text{with } prob. = inf\_prob \\ yield_t \times p, & \text{with } prob. = 1 - inf\_prob \end{cases} \quad (5)$$

For the no-control strategy, the grower faced the risk of infestation with the given probability (inf_prob). If the field was infested in the following week, the grower suffered from a yield loss from infestation (equation 5). Given that there has yet to be a consensus on predicting the yield loss when the field is infested by *D. suzukii* in the literature, we assumed the yield loss due to infestation was a fixed percentage of losses (inf_loss) and we included three hypothetical levels – 10, 30, and 50%. In other words, the yield loss due to infestation was assumed as dichotomous, such that the field was either infested with a fixed yield loss or not infested. We did not directly compute the severity of infestation in this analysis. Instead, the severity of infestation was included by considering three sets of scenarios with the different levels of the crop loss due to infestation (i.e., inf_loss equals to 10, 30, or 50%). The yield loss due to infestation also reflects the marketability of infested fruits, which generally depends on the grower's marketing channel. For example, export-oriented growers may face the worst-case scenario of 50% yield loss, given that the exporting market usually has very low tolerance to infested fruits, while some other processors may accept fruits with some infestation for producing byproducts (Drummond, pers. obs.).

$$Revenue_t = \begin{cases} E(Rev\_risk_{t+1}), & \text{if } strategy = no - control \\ yield_t \times p, & \text{if } strategy = early\ harvest \\ yield_{t+1} \times p - cost_{insecticide}, & \text{if } strategy = add.\ insecticide \end{cases} \quad (6)$$

The revenue at week *t, Revenue,* depending on the strategy chosen (equation 6). For the no-control strategy, the corresponding revenue, $E(Rev\_risk_t)$, was an expectation rather than a realized value due to the risk of infestation noted in equation 5. We assumed that the field was not infested during the week when the grower was making the decision of whether to apply insecticide, harvest, or do nothing (no-control), and the insecticide application strategy can effectively avoid infestation for the following week (Drummond et al. 2019). Thus, the risk of infestation only applied to the case of baseline no-control strategy, but not to the early harvest or insecticide application strategy. Each management strategy had a different harvest timing as listed in Table 1. Therefore, the yields used in the expected revenues for both no-control and insecticide application strategies were based on the approximated yield the following week ($t + 1$), while the yield used in the revenue of the early harvest strategy was based on the yield at the current given week (t). For the insecticide application strategy, the cost of insecticide application ($cost_{insecticide}$) was deducted from the revenue when harvesting at the following week. Since we assumed grower's management practice in the previous weeks was independent of the strategy chosen at this given week, we assumed that other production-related costs were the same for all management strategies and excluded them from the calculation of expected revenue.

The farm-gate price used in the revenue calculation was denoted as p in equations 5 and 6. According to U.S. Department of Agriculture (2019a), the average farm-gate price of wild blueberry has been fluctuating annually in recent years. Thus, we incorporated three market prices of wild blueberry in the analysis, which were \$0.57/kg (\$0.26/lb), \$1.14/kg (\$0.52/lb), and \$2.28/kg (\$1.04/lb), to understand how the outcome of the optimal management strategy may be affected by the market price. Given that most wild blueberries are sold in the processed (frozen) market, the within-season price is usually stable. Thus, we assumed the grower as a 'price-taker' in our analysis. This means that a single farm production did not affect the market price of the season.

Based on the above specifications, we employed Monte Carlo simulations with 1,000 iterations and calculated the average expected revenue for the baseline no-control scenarios. We then ranked the management strategies based on the expected revenue under scenarios with different values of p, inf_loss, and inf_prob for each percentage point of the ripeness level from 60% and beyond. The assumed parameter values used in the simulations were averaged for a typical farm in Maine, using data from the enterprise budgets and management tool (Yarborough and D'Appollonio 2017, Esau 2019), Drummond et al. (2019), statistics from U.S. Department of Agriculture (2019a), and personal communication with a wild blueberry production specialist (Yarborough, unpublished data). We assumed the baseline yield at full maturity was 4,484 kg/ha (4,000 lb/acre). The cost of one insecticide application was assumed to be \$75.86/ha (\$30.7/acre), including both material and application costs. The material cost of insecticide varies largely depending on the chosen product, so we selected the commonly used *D. suzukii*-targeted insecticides based on Drummond et al. (2018) to calculate the average. The application cost included other nonmaterial costs such as labor and machinery management calculated based on the enterprise budgets and management tool (Yarborough and D'Appollonio 2017, Esau 2019). We include a sensitivity analysis in the Supp Material (online only) to address the scenario with higher cost of insecticide application at \$197.7/ha (\$80/acre).

For the case of the organic production system, insecticide application may not be an option. Even when organically approved insecticides are available, many organic growers are philosophically opposed to their use in Maine wild blueberry (Drummond, pers. obs.). Thus, we compared the expected revenues between early harvest strategy and no-control strategy only. By the specifications in equations 3–6, the difference in the expected revenues of the two strategies was fully captured in the yield differences, given that the fixed market price could be canceled out and thus it did not affect the optimality of decisions. We identified the optimal harvest timing in terms of fruit ripeness percentage using the simulation results.

Results

Economic Significance of *D. suzukii* on the Wild Blueberry Industry in Maine

We summarized the calculation of the state-level production value for the wild blueberry industry in Maine and the value losses under three levels of hypothetical yield reductions (5, 10, and 30%) in Table 2. The aggregated state-level baseline (i.e., assumed no crop loss from *D. suzukii* infestation) value of production exceeded $22.8 million for the wild blueberry industry in Maine. The total state-level value of production could be broken down by farming system as low-input at $2.1 million, medium-input at 6 million, high-inputs at 10.9 million, and organic production at 3.8 million. Although the organic production system has the lowest share of total production area at 2% (138 ha) only, the higher average market price at $13.23 (compares with $0.57 for conventional production) contributed to the larger share in the aggregated state-level production value. With a 5% reduction in yield, the overall industry production value could be reduced by $1.1 million. With higher hypothetical yield reduction at 30%, the loss in state-level industry production value could increase to $6.86 million.

We presented the economic impacts regarding the increased frequency of insecticides from one to three applications per season for conventional production (Table 3). If conventional growers applied one additional insecticide on average, the estimated aggregated cost was around 0.5 million or 2.2% of the state-level value of production. If conventional growers on average applied two additional insecticides to control *D. suzukii*, the total costs increased by 1 million for the wild blueberry industry in Maine, which was about 4.5% of the total state-level value of production. Furthermore, the estimated state-level economic impact from two additional insecticide applications was of a similar magnitude to that of a 5% yield reduction ($1.1 million in Table 2) for the industry. These results showed that the economic impacts on the Maine wild blueberry industry may be significant if infestations were left uncontrolled or if growers attempt to avoid crop value loss by using insecticides. Nevertheless, a relevant issue is whether alternative sustainable control strategies such as early harvest can increase grower revenues. We addressed this question in the analysis below.

Farm-Level Economic Analysis

Results of the farm-level analysis are presented in Tables 4 and 5 and Fig. 1. In a given decision-making week, a grower from a typical wild blueberry farm in Maine observes the current percentage of fruit ripeness (horizontal axis in Fig. 1) and the cumulative male

Table 2. State-level effect of *Drosophila suzukii*-induced yield reductions in the absence of control

	Farming system				
	Low-input	Medium-input	High-input	Organic	Total (state-level)
Baseline value					
Total harvested hectares	1,376	2,270	3,096	138	6,880
Yield (kg/ha)	2,675	4,610	6,167	2,092	--
Price ($/kg)	$0.57	$0.57	$0.57	$13.23	–
Value of production (1,000$)	$2,110	$5,999	$10,943	$3,807	$22,859
Yield reduction at 5%					
Adjusted yield (kg/ha)	2,541	4,380	5,858	1,987	–
Adjusted value of production (1,000$)	$2,004	$5,699	$10,396	$3,617	$21,716
Losses in value (1,000$)	−$105	−$300	−$547	−$190	−$1,143
Yield reduction at 10%					
Adjusted yield (kg/ha)	2,408	4,149	5,550	1,883	–
Adjusted value of production (1,000$)	$1,899	$5,399	$9,848	$3,427	$20,573
Losses in value (1,000$)	−$211	−$600	−$1,094	−$381	−$2,286
Yield reduction at 30%					
Adjusted yield (kg/ha)	1,873	3,227	4,317	1,464	–
Adjusted value of production (1,000$)	$1,477	$4,199	$7,660	$2,665	$16,001
Losses in value (1,000$)	−$633	−$1,800	−$3,283	−$1,142	−$6,858

Table 3. State-level economic effect of insecticide applications targeting *Drosophila suzukii*

	Farming system (conventional only)							
	Low-input		Medium-input		High-input		Total (state-level)	
Counts of additional insecticide application per season	Costs (1,000$)	% to Total revenue	Costs (1,000$)	% to Total revenue	Costs (1,000$)	% to Total revenue	Costs (1,000$)	% to Total Revenue
1	$104	4.9	$172	2.9	$235	2.1	$512	2.2
2	$209	9.9	$345	5.7	$470	4.3	$1,023	4.5
3	$313	14.8	$517	8.6	$705	6.4	$1,535	6.7

Note: The '% to total revenue' refers to the percentage to total revenue of each system calculated in Table 2.

Table 4. Optimal management strategy for conventional production systems ranging from 60% fruit ripeness upward

	Yield loss once infested		
	10%	30%	50%
Price at $0.57/kg			
Low risk	No-control, harvest at full ripeness	No-control if fruit ripeness ≤97%, harvest otherwise	No-control if fruit ripeness ≤ 95%, harvest otherwise
Medium risk	No-control if fruit ripeness ≤96%, harvest otherwise	Apply insecticide if fruit ripeness ≤95%, harvest otherwise	Apply insecticide if fruit ripeness ≤95%, harvest otherwise
High risk	Apply insecticide if fruit ripeness ≤95%, harvest otherwise	Apply insecticide if fruit ripeness ≤95%, harvest otherwise	Apply insecticide if fruit ripeness ≤95%, harvest otherwise
Price at $1.14/kg			
Low risk	No-control, harvest at full ripeness	A mix of no-control and insecticide application when fruit ripeness ≤97%, harvest otherwise[a]	Apply insecticide if fruit ripeness ≤97%, harvest otherwise
Medium risk	No-control if fruit ripeness ≤97%, harvest otherwise	Apply insecticide if fruit ripeness ≤97%, harvest otherwise	Apply insecticide if fruit ripeness ≤97%, harvest otherwise
High risk	Apply insecticide if fruit ripeness ≤97%, harvest otherwise	Apply insecticide if fruit ripeness ≤97%, harvest otherwise	Apply insecticide if fruit ripeness ≤97%, harvest otherwise
Price at $2.28/kg			
Low risk	No-control, harvest at full ripeness	Apply insecticide if fruit ripeness ≤98%, harvest otherwise	Apply insecticide if fruit ripeness ≤98%, harvest otherwise
Medium risk	Apply insecticide if fruit ripeness ≤98%, harvest otherwise	Apply insecticide if fruit ripeness ≤98%, harvest otherwise	Apply insecticide if fruit ripeness ≤98%, harvest otherwise
High risk	Apply insecticide if fruit ripeness ≤98%, harvest otherwise	Apply insecticide if fruit ripeness ≤98%, harvest otherwise	Apply insecticide if fruit ripeness ≤98%, harvest otherwise

[a]The no-control strategy and the insecticide application strategy result in similar outcomes. See Fig. 1e for the average trend line.

Table 5. Optimal harvesting timing (in terms of fruit ripeness %) without the option of insecticide application

	Yield loss once infested		
Infestation risk	10%	30%	50%
Low risk	Full ripeness (100%)	97%	95%
Medium risk	96%	87%	80%
High risk	91%	76%	61%

D. suzukii trap capture. This grower uses *D. suzukii* trap capture to infer the risk level of getting infested (low, medium, or high). These factors along with the assumed level of yield loss and market price resulted in different expected revenue and grower can choose the best strategy accordingly. While we presented the expected revenue of each management strategy of the ripeness percentage from 60% onwards in Fig. 1, we summarized the optimal management strategy for conventional production that yielded the highest expected revenue at each ripeness level and identifies the ripeness level when the optimal strategy changed (i.e., the points of intersection between strategies in the corresponding subfigure in Fig. 1) in Table 4.

The results indicate that, for the scenarios with low risk and 10% yield loss if infested, the optimal management strategy was always the no-control strategy and harvesting at full crop maturity (Table 4). However, with an increased price for blueberry, or with the higher assumed yield loss once infested, the early harvest strategy before full crop maturity and applying insecticides became more optimal. For scenarios of $1.14/kg with 50% yield loss, $2.28/kg with 30% yield loss, and $2.28/kg with 50% yield loss, the insecticide application was the dominant strategy under all risk levels, as these scenarios reflected high value loss once infested. For the low-risk scenario of $1.14/kg with a 30% yield loss, the average revenue of no-control strategy was about the same as the extra insecticide application strategy, which is shown as an overlap in the red and lightest blue lines in the corresponding Fig. 1e. The simulation result suggests that, in most scenarios, the early harvest strategy was only optimal when fruit was very close to full maturity. For most cases of $0.57/kg, harvesting after the ripeness level reached 95% ripeness performed better than waiting to full fruit maturity (i.e., the early harvest strategy was the optimal strategy from 95% ripeness and beyond in those scenarios). However, in practice, 95% fruit ripeness may not be significantly different from full ripeness. In addition, results indicate that the insecticide application strategy was more optimal than early harvesting in most high-risk or high yield loss scenarios.

Regarding the case where insecticide application was not an option, we summarized the optimal harvest timing in terms of fruit ripeness percentage (Table 5; i.e., the points of intersections between strategies in Fig. 1 without considering the insecticide application strategy). The results show that only the low-risk scenario with a 10% yield loss had the same result with or without considering the option of the insecticide application strategy. In other cases, when the insecticide application strategy was excluded, harvesting earlier before full ripeness could yield higher expected revenues. Depending on the yield loss due to infestation, when the infestation risk was low, the optimal harvest ripeness was from 95% onward, which may not be significantly different from full ripeness in practice. For medium infestation risk, the optimal harvest timing ranged from 80 to 96% of ripeness. In the worst-case scenario with high infestation risk and 50% yield loss if infested, harvesting as early as the fruit ripeness reached 61% resulted in the highest expected revenue.

In addition, the relative difference in expected revenues from different risk scenarios are shown (Fig. 1). For example, if a grower assumes that the yield loss due to infestation was low at 10% (Fig. 1a, d, and g), the differences in the average revenues of the no-control strategy were relatively small between the three risk levels. But with higher assumed yield loss, the differences of expected revenues were larger between different risk levels when the grower waited to harvest (no-control strategy). Although the

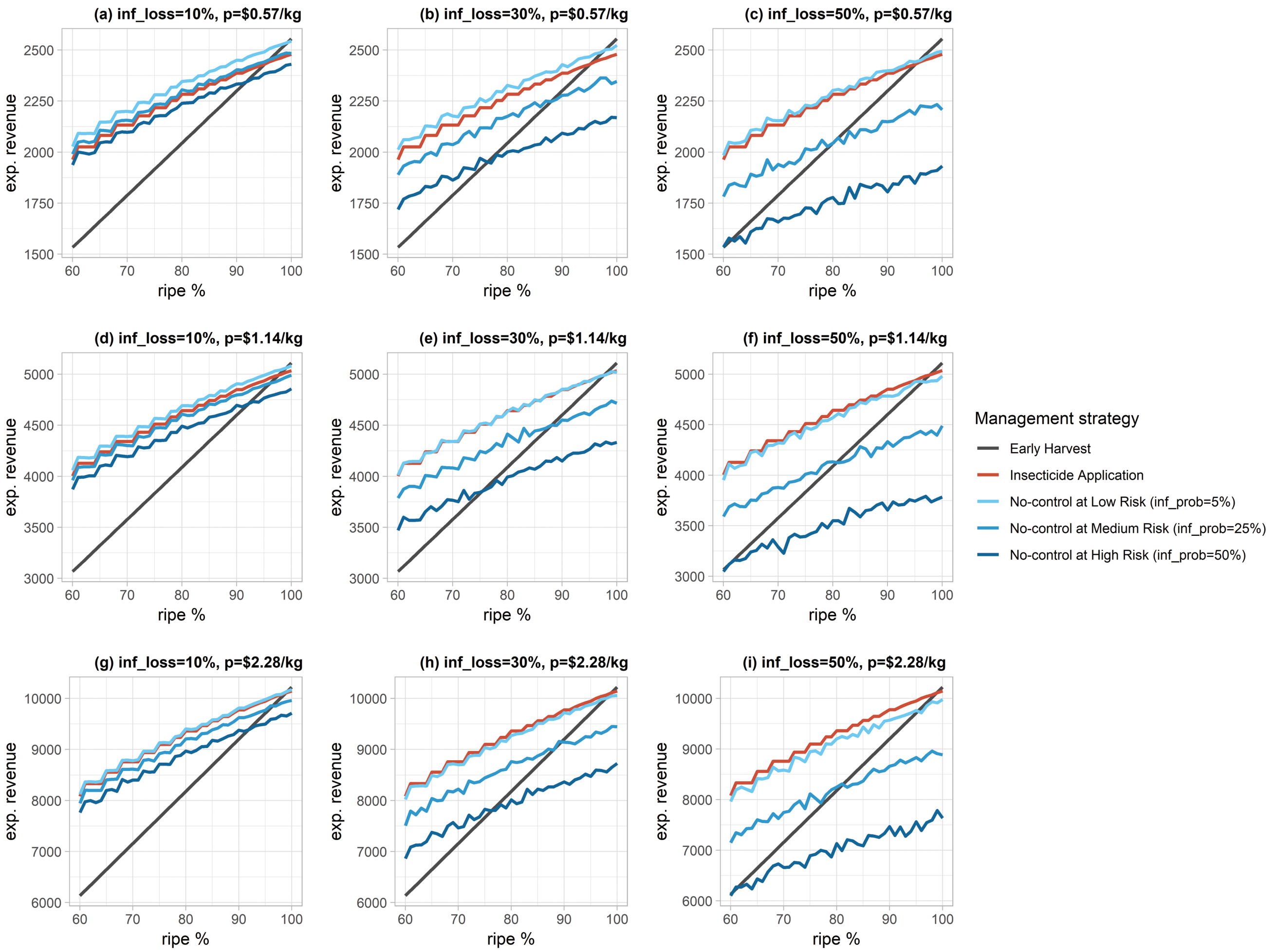

Fig. 1. Monte Carlo simulation results. For each subfigure, the horizontal axis indicates the percentage of fruit ripeness at a given week, whereas the vertical axis indicates the average expected revenue per hectare. The average revenues of the no-control strategy are shown as the three blue lines in the figures depending on the risk level. The revenues of the insecticide application strategy and the early harvest strategy are shown as the red and black lines, respectively. The revenue of early harvest strategy is a straight line in the subfigures, given that it is linearly related to the currently observed fruit ripeness, by definition (equations 3–5). Each subfigure corresponds to one market price (P = $0.57/kg, $1.14/kg, or $2.28/kg) and one yield loss once infested (*inf_loss* = 10, 30, or 50%). The following combinations for the subfigures are as follows: *inf_loss* = 10%, P = $0.57/kg (a); *inf_loss* = 30%, P = $0.57/kg (b); *inf_loss* = 50%, P = $0.57/kg (c); *inf_loss* = 10%, P = $1.14/kg (d); *inf_loss* = 30%, P = $1.14/kg (e); *inf_loss* = 50%, P = $1.14/kg (f); *inf_loss* = 10%, P = $2.28/kg (g); *inf_loss* = 30%, P = $2.28/kg (h); and *inf_loss* = 50%, P = $2.28/kg (i).

insecticide application was the optimal strategy for 1.14/kg with 50% yield loss, $2.28/kg with 30% yield loss, and $2.28/kg with 50% yield loss, the corresponding Fig. 1f, h, and i indicate that the revenue difference from insecticide application strategy to the no-control strategy was not large.

The results imply how the management optimality changed under different assumed parameter values. For example, assuming a 30% yield loss once infested, the optimal management option varied depending on the market price. Insecticide application became the dominant strategy when the market price was set at the highest level ($2.28/kg), but not when the market price was low, with low infestation risk. The higher market price implied higher expected revenue and thus demonstrated the importance of insecticide applications to protect the high-value crop from infestation. The expected revenues and standard deviations of the simulation results for selected benchmark ripeness levels were reported in Supp Table 1 (online only), and the sensitivity analyses with regards to a higher insecticide application cost were also reported (Supp Table 2 and Fig. 1 [online only]).

Discussion

The economic impact of *Drosophila suzukii* becoming an established insect pest of a cropping system can be complex and difficult to estimate. Our study demonstrates that this invasive pest has serious economic consequences to the production of Maine wild blueberry. A conservative state-level annual loss for this agricultural industry is estimated between $1.1 and 6.9 million. At the farm-level, we conducted economic analyses to evaluate optimal management decisions for *D. suzukii*. A multitude of scenarios were evaluated that included combinations of the expected price for the blueberry crop, level of expected infestation due to *D. suzukii*, the type of cropping system (organic to high capital input), and a range of spotted wing drosophila management tactics: no-control, early harvest, and action threshold based insecticide applications. Overall, we found that there is not one optimal management tactic for all production systems and economic price futures. Therefore, it is important for Maine wild blueberry growers not to assume that the best tactic for management of *D. suzukii* is to apply an insecticide, even if they are using a risk-based action threshold. Our discussion below highlights our findings and compares them to other findings in different crops in the United States and Europe.

The state-level economic impacts of *D. suzukii* were illustrated under specific market conditions and the results suggest that *D. suzukii* may bring high economic losses to the industry, as suggested by previous studies in other regions. For example, Bolda et al. (2010) and Walsh et al. (2011) assumed a 20% *D. suzukii*-induced yield loss for crops in the western United States and suggested that the total estimated value losses exceeded $511 million. In Europe, De Ros et al. (2015) and Mazzi et al. (2017) estimated large economic losses from *D. suzukii* on berry and cherry production. A recent study by Farnsworth et al. (2017) addressed the economic impacts of *D. suzukii* on the California raspberry industry with an elastic demand so that the estimation included changes in market price due to reduced production. In our study, we assumed a fixed market price in the state-level analysis because the majority of wild blueberries produced in Maine are sold to the frozen processed market rather than to the fresh market. As a result, the market price a grower received was relatively fixed within-season. In addition, we noted that the 2017 farm-gate prices used in this analysis were among the lowest prices for wild blueberries in recent years. If the market price returns to previous levels, the estimated state-level economic impacts from *D. suzukii* could be of a larger magnitude. Therefore, our estimates of the *D. suzukii* economic impacts for the industry were conservative.

One of the main implications of the farm-specific analysis is that a grower facing low market price in recent years, in most cases, is better off by doing nothing (no-control strategy) when the infestation risk is low at the decision-making week. Even under a high yield loss scenario (50% yield loss once infested), for the low market price at $0.57/kg, applying insecticide when the observed average male *D. suzukii* capture per trap was less than two male flies (Drummond et al. 2019) did not yield a higher average return. However, when the market price reached a higher level, meaning that the value of the crop was higher, applying insecticide became an economically optimal management strategy. This conclusion is in agreement with Goodhue et al. (2011), who analyzed high-value berry crops in California. They suggested that the costs of insecticide application and *D. suzukii*-targeted treatment were relatively small compared to the yield losses without *D. suzukii* management.

Another objective of the farm-level analysis was to quantitatively assess the economic impacts of the early harvest strategy, which avoids the use of insecticides. The result provided valuable information for organic growers where insecticide control may not be a feasible option. For example, if an organic grower expected a high yield loss (50%) once infestation was detected and faced a medium risk of infestation at the decision-making week, results suggested the grower should harvest right away as long as the fruit ripeness was over 80%. However, it should be noted that depending upon processor availability and timing of markets, early harvest may not be a viable strategy for all growers.

Previous literature that assessed the economics of Maine wild blueberry production focused primarily on comparing the performance of the four production systems (organic, low-, medium-, and high-input; Asare et al. 2017, Chen et al. 2017). Chen et al. (2017) simulated the price and yield risks and compared the expected profits for each production system, while Asare et al. (2017) analyzed the system performance with an econometric model of yield estimation considering the uncertainty of bee pollination. Both studies found that the organic production system was generally more profitable than the conventional production system in most scenarios due to the higher market prices. However, Asare et al. (2017) discussed the challenges for growers to adopt organic practices especially those concerning pest issues in wild blueberry production. With the lack of viable insecticide control, organic growers were under larger production risk than conventional growers. As Chen et al. (2017) and Asare et al. (2017) both discussed the risk associated with wild blueberry production from different aspects, this study extended the existing literature on wild blueberry management by addressing the pest infestation risk with different levels using the farm-level simulation analysis.

Although some conventional growers may follow a calendar-based insecticide application schedule to control for *D. suzukii*, Del Fava et al. (2017) pointed out that the optimal *D. suzukii* control option a grower should choose depended on the pest pressure one faced. Thus, incorporating the perceived risk levels in the simulations, the farm-level analysis considered the impacts of the pest pressure on grower's decision and shed light on the economics of *D. suzukii* pest management in Maine wild blueberry production. In addition, for the Maine wild blueberry growers that need to comply with more restricted insecticide application standards or more expensive materials based on their targeted marketing channels, the farm-level analysis provided insights on the optimal management strategies for different parameter values. We included a sensitivity analysis in Supplementary Material (Supp Table 2 and Fig. 1 [online only]) with a scenario of a higher insecticide application cost. Depending on the assumed parameter values, the cutoff point for performing early harvest and insecticide application under different infestation risk levels were quite different.

The yield loss due to infestation was one of the key elements to rank the management strategies using expected revenues. Although we assumed yield loss due to infestation as dichotomous (i.e., it was either infested with a fixed yield loss or not infested), one can view the level of yield loss as a tolerance level that growers may withstand. For example, a grower may have a postharvest sorting machine to sort out infested fruits or have buyers that are willing to buy fruits with some infestation for producing byproducts (Drummond, pers. obs.). In this case, the grower may have a higher tolerance level for *D. suzukii* infestation than the case where a grower must discard all fruit when detection of any level of infestation occurs. This last case is generally the case for exporting to foreign markets where the tolerance for infested fruit is relatively low. The 10% yield loss would, thus, be more applicable to the high tolerance grower, whereas the 50% yield loss would be more aligned with the export-oriented grower.

Because wild blueberry production possesses several unique characteristics, one should be cautious in generalizing the results in this study to the production of cultivated blueberries or other crops affected by *D. suzukii*. For instance, the majority of wild blueberries are harvested in one picking operation (Yarborough 2012). For cultivated blueberries, as growers harvest multiple times throughout one production season, studies showed that adopting a higher harvesting frequency can mitigate *D. suzukii* infestation (Farnsworth et al. 2017, Leach et al. 2018), and thus, early harvest is not a practical management strategy due to the differential cultivar ripening times. Furthermore, due to differences in marketing channels, compared with the cultivated blueberries (mostly for the fresh market), wild blueberry growers generally can tolerate a larger risk of infestation (mostly for the domestic processed frozen market). In general, the processor of the frozen market apply individually quick frozen (IQF) methods shortly after procuring the blueberries, so a low degree of infestation may be tolerated as the larval development will be terminated after IQF (Tochen et al. 2014, Ryan et al. 2016). In contrast, the fresh market buyers have a stricter standard in the appearance of fruits and usually demonstrate zero-tolerance for any infestation. In addition, risk-based action thresholds, which allow growers to optimize insecticide applications tailored to perceived risk, have been developed and are used in wild blueberry production, but not in cultivated blueberry production (Drummond et al. 2018, Drummond et al. 2019). Also, the within-season price variation for fresh market blueberries could be of large scale even on a daily basis (U.S. Department of Agriculture 2019b), which is not the case for the processed market. For fresh-market blueberry growers, the impact of temporal market prices on their expected revenues is likely to be a critical factor in deciding the optimal harvest timing, harvest frequency, as well as other pest management tactics.

There are several caveats that should be noted regarding this study. First, we drew the infestation probabilities from Drummond et al. (2019). Therefore, we did not consider external factors that may affect infestation probabilities such as the insecticide applications from adjacent neighboring farms or annual weather conditions. Future research should address possible externalities from neighboring blueberry crop fields and landscapes to explore region-level strategies to control *D. suzukii* that require collective action. Second, the analysis simplified the management options and assumed perfect insecticide efficacy, a case that we know is not always the case in wild blueberry production (Drummond et al. 2019). Future research should take into account the efficacy of alternative insecticides in controlling *D. suzukii*.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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