Quantifying a Quarantine Core Area Systems Approach for Mitigating the Risk of European Cherry Fruit Fly, *Rhagoletis cerasi* (L.), in New York State Cherry Fruit

Probabilistic Model Descriptions
EXECUTIVE SUMMARY

The detection of new exotic tephritid fruit flies such as the European cherry fruit fly (ECFF), *Rhagoletis cerasi* (L.), triggers the establishment of a 4.5 mile radius quarantine zone (roughly 81 sq. miles) around the detection. Typically, regulated host material is not allowed to move from the center core square mile of this quarantine zone. Here we created probabilistic models to evaluate the effectiveness of applying a systems approach to the core area to mitigate the risk of establishment of ECFF in new areas and to allow for limited movement of host material (i.e., cherries).

We tested the combination of the following three independent measures as components of the proposed systems approach:

- area of low pest prevalence, as determined by delimitation and regulatory trapping
- bait spraying, to kill flies
- limited distribution of fruit from quarantine areas, to keep potentially infested fruit from being transported to other cherry production areas

We modeled two different situations - first, for quarantine areas established based on detections in 2017 (Scenario 1), and second, for new quarantine areas from detections in 2018 (Scenario 2). This was done because ECFF population estimates depend on trapping densities and the trapping densities differ for established quarantine areas (delimitation) versus detection (regulatory) trapping in orchards where ECFF is not known to occur.

The model predicts the following: number of adults in the core area of the quarantine or new detection area; # adults remaining within 200 m of the detection (Scenario 2 only); # mated females; # mated females surviving and killed by natural mortality; potential # days of oviposition and the corresponding potential # eggs laid; realized # eggs oviposited after accounting for mortality from bait sprays; # viable larvae from hatched eggs; likelihood of infested fruit being misdirected to a new at risk area; # fruit with larvae surviving to adulthood; the probability of getting a mating pair from infested fruit being brought into a new at risk area if that happened at least once, and # years to the first mating pair. In Scenario 2 flies within and outside 200m are tracked separately, and two different models were run using densities of 5 or 2 traps per square mile. For Scenario 1, we also ran sensitivity analyses on certain parameters to evaluate the robustness of the predictions given available information.

The modeling showed that for Scenario 1 (quarantine areas identified in 2017), the systems approach reduced the risk of spread of ECFF to negligible levels, with \( p(\text{annual mating pair}) = 0.00002 \), and mean years to first mating pair in a new at risk area \( Y_{MP} = 50,000 \) years and only a 5 percent chance of that happening within 2,565 years. The most effective mitigations were bait spraying and limited distribution of fruit, which provided greater than 90 percent reductions of the extant population.

For Scenario 2 (2018 detections with new quarantine areas), the risk from flies outside 200m was negligible. Inside 200m, \( p(\text{annual mating pair}) = 0.00365 \) at 5 traps per square mile, and 0.0192 (1.9 percent) at 2 traps per square mile. The \( Y_{MP} \) for areas with 5 traps per square mile was 244 years, with a 5 percent chance of that happening within 13 years, while for areas with 2 traps per square mile, \( Y_{MP} \) was 53 years, with a 5 percent chance of that happening within 3 years. Going further, results indicate a 10 percent chance of a mating pair within 6 years, and a 20 percent chance of one within 12 years.

Although Scenario 1 was less risky than Scenario 2, both scenarios were found to provide acceptable levels of risk for the movement of cherries out of the core area under the proposed SA.
1. Introduction

1.1. Purpose and Scope

The objective of this report is to document the probabilistic models and the outcomes of these models used to evaluate the effectiveness of a quarantine systems approach for mitigating the risk of establishment of European cherry fruit fly (ECFF), *Rhagoletis cerasi* (L.), in new at-risk areas via movement of cherry fruit from the 0.5 mile radius core area of a domestic quarantine in northern New York State. The quarantine systems approach would allow for limited fruit distribution from the quarantine area to non-cherry producing areas as identified by the Agency.

The rationale behind the systems approach measures chosen, as well as any operational considerations or limitations, are beyond the scope of this technical modeling document.

1.2. Mitigations considered

All of the systems approaches tested below use the following three independent measures or components:

- **Area of Low Pest Prevalence (ALPP) Confirmation**, as determined by delimitation and regulatory trapping. Following the confirmation of a detected specimen as ECFF, delimitation trapping is implemented throughout the quarantine zone where trap densities are increased in a 100-50-25-20-10 array moving from the core square mile area surrounded by four, concentric, buffer square miles, respectively. Specific trapping is also required in the orchards, which can be called regulatory trapping, which includes at least 1 trap in every orchard and 2 traps for every 5 acres in general. See USDA ECFF New Pest Response Guidelines 2017-01 (PPQ, 2018).

- **Bait spraying**, to kill flies. The fruit fly quarantine area covering a 4.5 mile radius around all positive fruit fly sites will be treated according to CFR 301.32-10 (b) premise treatment, which is also referenced in the USDA ECFF New Pest Response Guidelines 2017-01 (PPQ, 2018).

- **Limited distribution**, to keep infested fruit from getting to hosts in other at-risk areas as defined by the Agency. Under the proposed systems approach, cherries would be allowed limited movement from any orchards within a 4.5 mile radius (81 sq. mile) quarantine zone, including the core square mile, if no flies were captured in the orchard and the prescribed premise treatment was followed.

Two different scenarios were modeled, as follows: 1) quarantine (core) areas established from 2017 detections, and 2) quarantine areas created because of one or more new ECFF detections in 2018. Different models are needed because ECFF population estimates depend on trap densities, which differ in the two scenarios.

1.3. Other possible mitigations
Cherry growers in New York and surrounding States routinely apply pesticides for other fruit fly pests, such as *Rhagoletis cingulata* (Loew) [cherry fruit fly], and *R. fausta* (Osten Sacken) [black cherry fruit fly] (Riedl and Kuhn, 1988). Depending on which sprays are used, those sprays could be partially or very effective against ECFF and provide additional safeguarding. However, these were not considered in estimating the effectiveness of the proposed systems approach because of the uncertainty of use, and the lack of direct efficacy data for ECFF for those compounds.

2. Standardized Methods

2.1. Model settings
All models were coded in spreadsheets and run using @Risk ver. 7.5 Professional (Palisade Corporation, 31 Decker Road, Newfield, NY 14867), a Microsoft Excel add-in. Unless otherwise specified below, simulation settings were as follows: number of iterations = 100,000; sampling type = Latin Hypercube; and random seed = 101.

2.2. Standard probabilistic functions

2.2.1. Binomial
The binomial process is common to the models below. In this process, *n* identical, independent trials are run, each one with the same probability of success, *p*, producing some number of successes, *s* (Vose, 2000):

\[ s = \text{RiskBinomial}(n, p) \]  

2.2.2. Beta
The value of *p* was sometimes determined from a beta distribution, which estimates the probability of success from the observed number of successes, *a*, and the number of trials, *b*, as follows:

\[ p = \text{RiskBeta}(a_0 + a, b_0 + b - a) \]  

where *a* and *b* are the prior values for *a* and *b*. Here we typically assumed a uniform prior, in which *a* = *b* = 1. This is a conservative approach because it uses a flat distribution with mean = 0.5 to inform the resulting “posterior” distribution.

2.3. Standard estimation processes

2.3.1. Central Limit Theorem
The central limit theorem (Vose, 2000) states that the mean of a set of *N* variables (where *N* is large) drawn independently will be Normally distributed. This usefully estimates the total sum from many lots of separate independent samples, such as, say, the total number of berries eaten by a large number of children, where berries eaten is a Normal distribution. The equation is as follows:

\[ X_{\text{tot}} = \text{RiskNormal}([N \times \mu],[\sqrt{N} \times \sigma]) \]
where $X_{\text{tot}}$ is the sum of interest, $N$ is the variable entity, $\mu$ is the mean of the Normal distribution, and $\sigma$ is the standard deviation of the distribution. The result is rounded to the nearest integer (not shown) for use in further calculations.

2.3.2. Probability of a mating pair

The probability of a mating pair ($p_{\text{mp}}$) being present depends on how many adult pests survive in the shipment. If zero or 1 adults survive, the probability is zero. Otherwise, the probability is calculated as follows (PERAL, 2005):

$$p(\text{mating pair}) = \frac{2^{A_{\text{surv}}-2}}{2^{A_{\text{surv}}}}$$  

[4]

This formula simply reflects the idea that, given $A_{\text{surv}} > 1$, with random sorting of males and females and an equal gender likelihood (i.e., $p_{\Phi} = p_{\Psi} = 0.5$), only two possible combinations exist in which no potential mating pair is possible: either all adults are males or all adults are females. Therefore, $p(\text{mating pair})$ is the number of possible combinations of numbers of males and females minus two, divided by the total number of combinations.

2.3.3. Mating pair formation

We modeled this as a binomial process (Eqn. 1), with $n = 1$ and the likelihood = $p(\text{mating pair})$ (Eqn. 4). The function returns a 1 if successful (mating pair present) or a zero if not. The model tracks this process and the resulting mean over all iterations (i.e., $x$ successes divided by the no. of iterations), $p_{\text{ann}}$, estimates the annual probability of a mating pair being present.

2.3.4. Years to first mating pair

We use $p_{\text{ann}}$ in the negative binomial function to estimate the number of years, $Y$, that will pass until the first mating pair occurs (Vose, 2000). The equation is as follows:

$$Y = 1 + \text{RiskNegbin}(1, p_{\text{ann}})$$  

[5]

Note that the mean years until the first mating pair occurs is equal to the reciprocal of $p_{\text{ann}}$.

3. Model specifications

3.1. Model description: Systems approach for 2017 quarantine areas [Scenario 1]

First we focus on the systems approach applied to quarantine areas that were established based on ECFF detections in 2017. Hereafter this will be referred to as Scenario 1.

Flies are most likely to emerge in the core area, which has the greatest density of traps in the regulatory trapping procedure (PPQ, 2018). The model predicts the number of adults in the core area of the quarantine, the number of mated females, the number of mated females surviving and killed by natural mortality, the potential number of days of oviposition and the corresponding potential number of eggs laid, the realized number of eggs due to mortality from bait sprays, the number of viable larvae from hatched eggs, the likelihood of infested fruit being misdirected to an endangered area, the number of fruit with larvae surviving to adulthood, the probability of getting a mating pair from infested fruit at the endangered area and if that happened at least once, and finally the number of years to the first mating pair (Fig. 1). We have assumed that the core
area is sited in a cherry grove with ample fruit production. Note that numbers of ECFF flies and infested fruit are equivalent, because the species lays one egg per fruit (below). We summarize below the parameter values and functions used, as appropriate (Table 1).

3.1.1. Adults in the core area
One of the requisites for the systems approach in Scenario 1 is that no ECFF have been trapped in the core area of the quarantine in 2018 before harvest. The greater trapping density in place (100 traps per square mile) allows us to estimate a lower population size than in Scenario 2, likely making these areas less risky.
Fig. 1. Diagram showing state variables and transition probabilities/factors for modeling the risk of European cherry fruit fly in cherries in New York under a systems approach, specifically for Scenario 1: quarantine areas established based on 2017 detections. Solid lines indicate transfer of individuals while dashed lines indicate transfer of information.
Table 1. Model nodes and parameters in the systems approach for Scenario 1, for fruit from quarantine core areas.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Function</th>
<th>Parameters</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adult flies in core area (no.)</td>
<td>Histogram</td>
<td>$x_{\text{Min}} = 1; x_{\text{Max}} = 345; p$ values as in Fig. 3</td>
<td>Separate simulation (see text) based on results using Manoukis et al., 2014</td>
</tr>
<tr>
<td>1a</td>
<td>Adult flies remaining in core area (no.)</td>
<td>Assumption</td>
<td>Incoming and outgoing flies are equal in number</td>
<td>Relatively low mobility of ECFF around hosts (Fletcher, 1989; Lux et al., 2016)</td>
</tr>
<tr>
<td>2</td>
<td>Female adults in core area (no.)</td>
<td>Binomial (Eqn. 1)</td>
<td>$p(\text{female}) = 0.5$</td>
<td>e.g., Lux et al., 2016</td>
</tr>
<tr>
<td>3</td>
<td>Mated females (no.)</td>
<td>Assumption</td>
<td>$p(\text{mating}) = 1$</td>
<td>Note: 119/128 mated females captured (Katsoyannos et al., 2000)</td>
</tr>
<tr>
<td>4</td>
<td>Mated females surviving and killed by natural mortality, in specified intervals (no.)</td>
<td>Binomial (Eqn. 1) and Multinomial</td>
<td>$p(\text{natural mortality}) = 0.434 (8-45d); 0.083 (8-20d); 0.209 (21-30d); 0.103 (31-40d); 0.040 (41-45d)$</td>
<td>Moraiti et al., 2012</td>
</tr>
<tr>
<td>5</td>
<td>Potential ovipositing days by mated females, in specified increments (d)</td>
<td>Discrete (with arithmetic)</td>
<td>Total days = 38; From above, Period 1 = 13 d; Pers. 2 and 3 = 10 d; Per. 4 = 5 d</td>
<td>Moraiti et al., 2012</td>
</tr>
<tr>
<td>6</td>
<td>Total potential eggs oviposited, $N_{\text{pot}}$ (no.)</td>
<td>Central limit theorem (Eqn. 3; e.g., Vose, 2000)</td>
<td>Eggs per day per female: mean ($\mu_{\text{egg}}$) = 5.085, standard deviation ($\sigma_{\text{egg}}$) = 0.676</td>
<td>Moraiti et al., 2012</td>
</tr>
<tr>
<td>7</td>
<td>Total eggs oviposited in fruit despite bait spraying, $N_{\text{ovi}}$ (no.)</td>
<td>Multiplication (rounded to nearest integer)</td>
<td>Proportion of infested fruit after bait spraying: Triang with minimum = 0.0072, most likely = 0.0301, and maximum = 0.0460</td>
<td>Köppler et al., 2008</td>
</tr>
<tr>
<td>8</td>
<td>Fruit with viable eggs [larvae], $N_{L}$ (no.)</td>
<td>Multiplication (rounded to nearest integer)</td>
<td>$p(\text{hatch})$: Beta distribution with $a = 11,310$, and $b = 12,326$</td>
<td>Prokopy and Boller, 1970</td>
</tr>
<tr>
<td>9</td>
<td>Infested fruit misdirected to endangered area, $N_{\text{EA}}$ (no.)</td>
<td>Binomial (Eqn. 1)</td>
<td>$n = N_{L}$, $p(\text{misdirection}) = 0.00116$</td>
<td>PPQ, 2001</td>
</tr>
</tbody>
</table>
We estimated the number of adult flies in the core area using above assumption and results from a fruit fly trapping simulation model (Manoukis et al., 2014) parameterized (with attractiveness and trap density) for this situation. The results of that model are estimated cumulative likelihoods of capturing a fly on a particular trapping day. Model parameters were based on trapping density and trap attractiveness. Trapping density was for ‘regulatory trapping’ in the core area of 100 traps per square mile. We have assumed use of the standard trap for ECFF, which is a yellow panel trap (“protein-baited yellow sticky card with a lure of ammonium acetate in a polycon dispenser”; PPQ, 2018). Based on reports from various researchers (e.g., Lux et al., 2016), they used a value of around five percent attractiveness.

We used one of the \( p(capture) \) values in a separate simulation model (details available upon request) to determine the number of flies present that led to a detection. We chose the \( p(capture) \) value from day 8 (\( = 0.0358 \)) because that is the day on which oviposition typically begins for an ECFF female (Moraiti et al., 2012). Values for later days gradually increase, so using the value from day 8 was a conservative choice (i.e., population maximizing). The model simulates each fly successively in a binomial process (Eqn. 1) with \( n = 1 \) and \( p = p(capture) \) until a fly is detected (\( s = 1 \)). The estimated population size for no detection, as in our proscribed systems approach (above), is then that number fly minus one (i.e., if the 5th fly was captured, the estimated population size is 4, the largest size giving no detection). The simulated values describe the distribution for total population size, which we expressed in a histogram for the main model, as follows:

\[
N_A = \text{RiskHistogrm}(x_{\text{Min}}, x_{\text{Max}}, [p \text{ values}])
\]

where \( N_A \) is the number of adults, \( x_{\text{Min}} \) is the minimum, \( x_{\text{Max}} \) is the maximum, and the \( p \) values indicate the likelihoods for each interval between the minimum and maximum. In Scenario 1, the mean for that distribution was 26.9 flies, and the maximum value was 341 (Fig. 3).

### 3.1.2. Females in the core area

We predicted the number of males and females based on an equal sex ratio (i.e., \( p(\text{female}) = 0.5 \)) (e.g., Lux et al., 2016). The number of females, \( N_\varphi \), was a binomial (Eqn. 1).

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1 In @Risk, the function used is spelled as shown: ‘RiskHistogrm’
3.1.3. Females in the core area after dispersal
ECFF tend to not disperse very far when suitable hosts are available (e.g., Boller et al., 1971; Fletcher, 1989). Given this and the presence of hosts other than cherries (e.g., honeysuckle) in the area (PPQ Field Operations, personal communication), we assumed that the number of flies entering the area would equal the number departing, which is to say very few flies will move in or out of the core area. Lux et al. (2016) made the same assumption in their model. Hence, the number in the area after dispersal was simply the total originally estimated to be there, $N_{♀}$.

3.1.4. Females killed by natural mortality
From emergence to the end of oviposition, some female flies will die of natural causes. We used results from Moraiti et al. (2012) to estimate probabilities for four different time periods, $t$, from the start of oviposition on day 8, to the end of oviposition on day 45 (Table 2). Very little mortality occurs before day 8. Values were digitally interpolated from Fig. 3 (‘Allopatric populations,’ Stecklenburg strain) in Moraiti et al. (2012).

<table>
<thead>
<tr>
<th>Time span (start-end days)</th>
<th>$p$(natural mortality)</th>
<th>Oviposition days (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-20</td>
<td>0.083</td>
<td>13</td>
</tr>
<tr>
<td>21-30</td>
<td>0.209</td>
<td>10</td>
</tr>
<tr>
<td>31-40</td>
<td>0.103</td>
<td>10</td>
</tr>
<tr>
<td>41-45</td>
<td>0.040</td>
<td>5</td>
</tr>
<tr>
<td>Total (8-45)</td>
<td>0.434</td>
<td>38</td>
</tr>
</tbody>
</table>
In the model, we first estimated the total number of flies killed naturally, \( M_{\text{tot}} \), in a binomial process (Eqn. 1) with \( N_\text{♀} \) and total \( p \) (natural mortality) = 0.434 (Table 2). Then we used a multinomial process (e.g., Vose, 2000) to distribute those flies amongst the different time periods. The multinomial process (Eqn. 1 used sequentially) parameters are \( n = \) remaining flies, \( M_{\text{net}} \), and \( p = p_{\text{eff}} \), the effective probability. The function for \( M_{\text{net}} \) is as follows:

\[
M_{\text{net},i} = M_{\text{tot}} - \sum(M_1, ..., M_{i-1})
\]  

[6]

where \( i \) is the current time period, and the sum is for any flies apportioned to previous periods.

The function for \( p_{\text{eff}} \) is as follows:

\[
p_{\text{eff},i} = p_i / (\sum(p_i, ..., p_4))
\]  

[7]

where the sum is from \( i \) to period 4. Collectively, these procedures apportion exactly \( M_{\text{tot}} \). From this we calculate numbers of females that lived to each time span, \( N_{\text{surv},i} \), or over the entire period (>45 d), \( N_{\text{surv,tot}} \), which is necessary to estimate days of ovipositing.

3.1.5. Potential days laying eggs
In the model we first estimate the total potential number of oviposition days for all female flies before accounting for the effects of bait spraying. That was because the impacts of bait spraying were reported as reductions in infestations rather than as mortality estimates (see below).

The number of oviposition days in each time span \((i)\), \( N_{d,i} \), was the sum of days accrued by flies surviving to that point. The overall oviposition start and length (both number of days) was determined from Fig. 4 in Moraiti et al. (2012) (Table 2). Surviving flies, \( N_{\text{surv,tot}} \), laid eggs for the full 38 days, so the total days for those flies, \( D_{\text{surv}} \), was the product of 38 and \( N_{\text{surv,tot}} \).

Killed flies laid eggs for some portion of the period in which they died. Because the number of flies was not too great, we predicted life spans individually. The total number of days each fly lived in the period \((D_i)\) in which it died was a discrete function with equal probabilities for each day, as follows:

\[
D_i = \text{RiskDiscrete}([d \text{ values}], [\text{weights}])
\]  

[8]

where \( D_i \) is the number of days of ovipositing, \( d \) values are the array of days in the \( i \) period (Table 2), and weights are all 1 (i.e., equal probabilities). The total days of ovipositing by an individual fly \((\gamma)\) was therefore:

\[
D_{\text{tot},\gamma,i} = D_i + \sum(D_{\text{tot},\gamma,1}, ..., D_{\text{tot},\gamma,i-1})
\]  

[9]

where the sum over \( i \) is for the total days in preceding periods. [Note that our calculations assume the fly oviposited on the day it died.] The total number of days of ovipositing in a period by all flies is the sum for all the individuals \((\sum(D_{i,tot,\gamma}) \text{ over all } \gamma)\), and the grand total \((D_{\text{ovi}})\) is the sum of potential days for all surviving flies \((D_{\text{surv}})\) and for all killed flies over all periods \((\sum(D_{i,tot}) \text{ over all } i)\).
3.1.6. Total potential eggs laid

The reported estimate of how many eggs each ECFF female lays per day is somewhat vague. For example, Lux et al. (2016) report 0-10 per day. Ideally, we needed estimates for a mean and standard deviation that could be used in the Central Limit Theorem. Starting with the total number of eggs per female and standard errors reported in Moraiti et al. (2012), we generated upper and lower confidence intervals ($\alpha = 0.05$). Dividing each of those values by the duration (38 d) gave estimates of mean daily eggs laid, $\mu_{\text{egg}}$, (5.09) and upper and lower limits. Finally, we input those limits in a uniform distribution to estimate standard deviation, $\sigma_{\text{egg}}$ (0.676). The resulting distribution (Table 1) has 90 percent of its values between 3.97 and 6.20 (Fig. 4).

In the model, we estimated the total potential eggs ($N_{\text{pot}}$) laid using the Central Limit Theorem (Eqn. 3) with parameters $\mu_{\text{egg}}$ and $\sigma_{\text{egg}}$. Lastly, we note that ECFF most likely only oviposit one egg per fruit (Fletcher, 1989), so this value for potential eggs is functionally equal to the number of potential infested fruit.

![Figure 4](image)

**Figure 4.** Normal distribution for mean eggs laid per day by European cherry fruit fly females, based on data from Moraiti et al. (2012).

3.1.7. Infested fruit after bait spraying

In bait spraying, flies (male and female) are attracted to an insecticide via bait, often protein and sugar, resulting in their death. The data we found on its effects on ECFF populations was reported in terms of percent infested fruit with and without bait spraying (Köppler et al., 2008). One of the insecticide rates they reported—a 20% formulation of GF-120—conformed roughly to the protocol for using GF-120 against ECFF here (Vargas, personal communication). The control value was 59.8 percent infested, and bait spraying reduced that to 1.8 percent, which is a nearly 97 percent reduction. We used these values to estimate the mean reduction, and digitally estimated upper and lower values from the figure (‘Fig. 1’ in Köppler et al., 2008). This gave us parameters for a triang distribution (e.g., Vose, 2000) for the percentage of infested fruit after
accounting for bait spraying, $Q_{bs}$ (Table 1). The number of fruit with actual oviposited eggs, $N_{ovi}$, was the product of $N_{pot}$ and $Q_{bs}$, rounded up to the nearest integer. For reference, we calculated the proportional mitigation effect due to bait spraying as $(N_{pot} - N_{ovi}) / N_{pot}$. 

3.1.8. Fruit with viable larvae
We estimated the probability of eggs to hatch, $p$(hatch), and presumably become larvae, as a beta distribution [Eqn. 2]. The parameters for the distribution were based on trial results published by Prokopy and Boller (1970) (Table 1). Using data from just the first five weeks of life, the mean of the distribution for $p$(egg hatch) was 0.9175, and 90 percent of the values were between 0.9134 and 0.9215 (Fig. 5). The number of fruit with viable larvae, $N_{L}$, was the product of $p$(hatch) and $N_{ovi}$, rounded up to the nearest integer. For reference, we calculated the proportional mitigation effect due to non-hatching as $(N_{ovi} - N_{L}) / N_{ovi}$.

Figure 5. Probability distribution for ECFF egg hatch based on trial data from Prokopy and Boller (1970).

3.1.9. Infested fruit misdirected from distribution area
The above calculations estimate the risk of shipped fruit being infested with ECFF larvae, but the risk of establishment is negligible unless those fruit move to endangered areas. Thus, we also estimated the number of those fruit that might be misdirected (e.g., smuggled, sent to a wrong destination) to cherry production areas outside the immediate area ($N_{EA}$). One important factor is that cherry-producing areas are likely to have negligible demand for cherries from outside the area, which should significantly limit the potential for infested fruit to move to such places. We have no direct information about this, so we based our estimate on data collected several years ago when avocados from Mexico had a similar restricted distribution (Table 3; PPQ, 2001. Despite not being about cherries, the data reflect real supplier/consumer behavior around illicit movement of produce, and we think the low probability demonstrated is likely to generally represent the likelihood of cherries moving—presumably despite a lack of demand—to other cherry-producing locales. We used that data similarly for a systems approach model for the
distribution of quarantined citrus (PPQ, 2015). For the distribution we calculated a mean proportion of fruit misdirected (= 0.00116), and used that as $p$ in a binomial process (Eqn. 1) with $n = N_L$. We used a binomial process to increase the chance of multiple infested fruit being misdirected, despite the resulting increase in uncertainty. When the mean probability is as low as this estimate, multiplication and rounding up (e.g., ‘infested fruit after bait spraying’) might minimize the resulting totals. For reference, we calculated the proportional mitigation effect as $(N_L - N_{EA}) / N_L$.

3.1.10. Fruit with larvae surviving to adulthood
Natural mortality as larvae develop to adulthood can be significant. We estimated the total mortality of this process based on data from Boller and Remund (1989). Rather than report stage-to-stage probabilities, however, the authors presented data as mean numbers of individuals at each stage for three years of trials (1971-73). Larvae dropping from fruit to become pupae in the group had only a single observation ($\rho = 0.63$), so we assumed complete survival at that stage because it was not replicated. We used values for the mean transition probabilities and minima and maxima (Table 3) to parameterize triang distributions (e.g., Eqn. 11) and simulated the outcomes for a starting population of 10,000 pupae (more detail available upon request). The resulting distribution for $\rho$(survival larva-adult) had mean $= 0.053$, minimum $= 0.012$, and maximum $= 0.131$ (Fig. 6). We used these as parameters in a Pert (skewed) distribution (e.g., Vose, 2000), which had 90 percent of its values between 0.042 and 0.154. For reference, we calculated the proportional mitigation effect as $(N_{EA} - N_A) / N_{EA}$.

3.1.11. Mating pairs and years to first mating pair
We calculated the probability of a mating pair (Eqn. 2) based on the number of adults in the endangered area, assuming they had all arrived together in the same shipment and stayed in proximity to each other. We then used that probability to determine if a mating pair resulted, using a binomial process (Eqn. 1). The mean of that binomial is the model estimate for the annual probability of getting a mating pair in an endangered area from infested fruit, $p$(annual mating pair). Once that value had been found, we re-ran the simulation to find $Y_{MP}$, years to first mating pair at an endangered area (Eqn. 4).

Table 3. Probabilities of survival of European cherry fruit flies for different life stage transitions over different time spans (Boller and Remund, 1989).

<table>
<thead>
<tr>
<th>Stages</th>
<th>Percent survival</th>
<th>1971</th>
<th>1972</th>
<th>1973</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larvae-early Pupae</td>
<td>0.484</td>
<td>0.230</td>
<td>0.421</td>
<td>0.379</td>
<td>0.230</td>
<td>0.484</td>
<td></td>
</tr>
<tr>
<td>Early-late Pupae</td>
<td>0.563</td>
<td>0.253</td>
<td>0.408</td>
<td>0.253</td>
<td>0.563</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late Pupae-Adult</td>
<td>0.258</td>
<td>0.855</td>
<td>0.652</td>
<td>0.588</td>
<td>0.258</td>
<td>0.855</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Scenario 1 sensitivity analyses

We tested changes to four model estimates specific to Scenario 1 to determine the potential impact from any specification errors. The standard procedure was to increase or decrease (as appropriate) parameter values by 50 percent and re-run simulations (same simulation specifications) to compare results. In every case, we modified the model as necessary to avoid errors and to account for, for example, greater numbers of flies when predictions were made for individual flies (e.g., §3.1.5). In some cases we also tested parameter/variable increases of 100 percent.

3.2.1. Population estimate
The initial prediction for the number of flies in the core area is obviously a key factor, and it also was important to test this estimate because of the uncertainties involved in its estimation (§3.1.1). We tested this for increases of both 50 and 100 percent.

3.2.2. Bait spraying
The data on impacts of bait spraying on ECFF were fairly robust, but we found no direct mortality data (§3.1.6). Therefore, we tested the effect of a 100 percent decrease in the efficacy of bait spraying (i.e., doubled the likelihood of eggs being oviposited).

3.2.3. Limited fruit distribution
The rationale behind this measure seems very robust, because moving NY cherries to sell in another cherry-producing area (e.g., Washington state) seems extremely unlikely to happen from the standpoints of both demand and potential profits. Still, because our estimate came from data
on the misdirection of avocados, we tested both 100 and 500 percent increases in the likelihood of cherries to be sent to an endangered area.

3.2.4. Larval survivorship to adulthood
Expecting individual mortality of larvae as they develop into pupae and then adults is reasonable, and we found relatively good data for estimating this (§3.1.10). Because we had to create a separate simulation model to generate transition probabilities, however, we tested a 100 percent increase in survivorship via this process.

3.2.4. Combination of all four factors
For reference, we simulated all four factors above combined at once. Specifically, we tested the combination of 1) a 50 percent increase in fly population, 2) a 100 percent decrease in bait spraying efficacy, 3) a 100 percent increase in the likelihood of fruit to be misdirected to an endangered area, and 4) a 100 percent increase in larval survivorship to adulthood.

3.3. Model description: Systems approach for 2018 quarantine areas [Scenario 2]
Here we focus on the systems approach applied to quarantine areas that were established based on new, in-season ECFF detections in 2018. Hereafter this will be referred to as Scenario 2, specifically referencing either 5 or 2 traps per square mile (below). Besides the initial population estimate, only a few model processes differed from those in Scenario 1 (Fig. 1, Table 1), and those are all described below (Table 4).

3.3.1. Adults in the area
In this case, flies have been detected in 2018 in areas where trap densities are much smaller than for regulatory trapping (§3.1.1). Trap densities in non-quarantine-affected cherry-growing areas will be 5 traps per square mile (Stewart, personal communication). Beyond those areas, however, trap densities may be as low as 2 traps per square mile. As above, we assume that bait spraying has started before detection.

The trapping model was parameterized as before, but with the lower trapping density of 5 or 2 traps per square mile. As in Scenario 1, we used the \( p(\text{capture}) \) value from day 8 () for the population size simulation model. The model sequentially tested adult flies to see if they were captured or not. In Scenario 2, the number of the fly captured (say, number 50) becomes the population estimate for that iteration, since no previous flies were detected.

For 5 traps per square mile, the mean fly population size \( N_A \) was 435, and 90 percent of values were between 23 and 1,303 (Fig. 7A). For 2 traps per square mile mean \( N_A \) jumped to 1,084, and 90 percent of the values were between 57 and 3,258 (Fig. 7B). Note that these estimates hold only if no more than one fly is detected in the new area. Each successive trapped fly would roughly increase the estimated size by a factor of one (i.e., three trapped flies means 3 times the baseline estimate).
**Table 4.** Model nodes and parameters in the systems approach for Scenario 2, for fruit from new (2018 detections) quarantine core areas.

<table>
<thead>
<tr>
<th>Description</th>
<th>Function</th>
<th>Parameters</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult flies in core area (no.)</td>
<td>Histogram</td>
<td>See Fig. 7</td>
<td>Separate simulation (see text) based on results using Manoukis et al., 2014</td>
</tr>
<tr>
<td>Adult flies within 200 m and beyond 200 m in area (no.)</td>
<td>Binomial</td>
<td>( p(\text{dispersal}) = 0.0858 )</td>
<td>Boller et al., 1971</td>
</tr>
<tr>
<td>Potential ovipositing days by mated females, in specified intervals (d)</td>
<td>Within 200 m:</td>
<td>Mean days (SD):</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Central Limit</td>
<td>8-20d = 7 (3.74)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Theorem</td>
<td>21-30d = 5.5 (2.87)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outside 200 m:</td>
<td>31-40d = 5.5 (2.87)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Discrete (see Table 1)</td>
<td>41-45d = 3 (1.41)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7.** Probabilities for the number of adult European cherry fruit flies in the field for either areas with A) 5 traps per square mile, or B) 2 traps per square mile. The red arrow approximately indicates the mean of the distribution.
3.3.2. Adults within and outside 200m of the detection
Because of lower trap densities in Scenario 2, and the possibility of detections not in the immediate vicinity of hosts, we cannot be quite as sure that flies do not disperse. We estimated the number of flies dispersing 200 m or more from the detection as a binomial process with \( n = N_A \), and \( p = \text{probability of 200m+ dispersal, } p(\text{disperse}) \). We estimated \( p(\text{disperse}) \) to be 0.086, based on mark-recapture data for ECFF (Boller et al., 1971). In the model we tracked flies within and outside 200 m separately.

3.3.3. Potential days laying eggs
There were no model differences in this section for intervals or numbers of days in each. However, fly populations within 200m of the detection became too great to get individual estimates. In those cases we used the Central Limit Theorem (Eqn. 3), with means and standard deviations that corresponded to the appropriate interval (Table 4). The number of potential days of ovipositing was the subtotal from the Central Limit Theorem calculation for the current interval, plus the product of the number of flies killed in this interval and the number of days for any preceding intervals.

4. Results and Discussion

4.1. Scenario 1 systems approach results
The mean number of mated female flies in the core area was about 14 (max = 161), and mean number of eggs oviposited (accounting for bait spraying) was equal to 59.1.

In 100,000 iterations of the simulation model, one or more mating pairs of ECFF only occurred in endangered areas twice, giving \( p(\text{annual mating pair}) = 0.00002 \). The associated mean years to first mating pair at an endangered area, \( Y_{MP} \), was 50,000 years, with only a 5 percent chance of that happening within 2,565 years (Fig. 8). The combination of mitigations proposed in this systems approach seem to very effectively reduce the risk of establishment of ECFF in other cherry-producing areas via fruit from the quarantined area in NY.

Reference calculations for the risk reductions provided by different risk measures indicated that bait spraying and limited distribution of fruit provided greater than 90 percent reductions on average (Table 5). In addition, the biological process of larval survivorship to adulthood also reduced populations by over 90 percent. Lost viability of eggs only decreased populations by about 6 percent, since egg viability is high.

<table>
<thead>
<tr>
<th>Measure or Process</th>
<th>Mean population reduction proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bait spraying</td>
<td>0.971</td>
</tr>
<tr>
<td>Egg viability</td>
<td>0.059</td>
</tr>
<tr>
<td>Limited distribution of fruit</td>
<td>0.999</td>
</tr>
<tr>
<td>Larval survival to adulthood</td>
<td>0.908</td>
</tr>
</tbody>
</table>

Table 5. Mean proportional population reductions given by different risk measures or biological factors in the proposed systems approach for European cherry fruit flies in NY cherries.
4.2. Scenario 1 sensitivity analysis results

4.2.1. Population estimate
A 50 percent increase in the number of flies in the core area only increased $p_{\text{annual mating pair}}$ to 0.00003 (3 occurrences in 100,000 iterations) (Table 6). That gave mean $Y_{MP}$ of 33,334 yr, with a 5 percent chance of one or more mating pairs happening within 1,710 yr. A 100 percent increase in the number of flies in the core area increased $p_{\text{annual mating pair}}$ to 0.00008 (quadruple the standard value). Still, this only gave a mean $Y_{MP}$ of 12,500 yr, with a 5 percent of a mating pair within 642 yr.

Overall, the risk remained negligible despite the tested increases. Extrapolating from these results, we might expect the risk to become problematic only if the population estimates were off by a factor of 25. In other words, in Scenario 1 the risk may become significant only if the mean number of flies in the core area increase from about 27 flies (§3.1.1) to 675 flies. Early season regulatory trapping is likely to indicate if estimates are that far off, but regardless fruit is not approved to move under the systems approach unless zero flies have been trapped before harvest in the core area.

4.2.2. Bait spraying
A 100 percent decrease in the efficacy of bait spraying caused the $p_{\text{annual mating pair}}$ to increase to 0.00009. Still, mean $Y_{MP}$ was only 11,111 yr, and the 5th percentile equaled 570 years.
Table 6. Sensitivity analysis results for percentage increases/decreases of different model processes, and the combination of four of them, in terms of the probability of getting one or more mating pairs in an endangered area, $p$(annual mating pair), and years to first mating pair of European cherry fruit fly in an endangered area, $Y_{MP}$, via cherries from a NY quarantine area.

<table>
<thead>
<tr>
<th>Process</th>
<th>Change (+/- %)</th>
<th>$p$(annual mating pair)</th>
<th>$Y_{MP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Baseline Model</td>
<td>—</td>
<td>0.00002</td>
<td>50,000</td>
</tr>
<tr>
<td>1. Population estimate</td>
<td>+ 50</td>
<td>0.00003</td>
<td>33,334</td>
</tr>
<tr>
<td>2. Bait spray efficacy</td>
<td>− 100</td>
<td>0.00009</td>
<td>11,111</td>
</tr>
<tr>
<td>3. Fruit misdirection</td>
<td>+ 100</td>
<td>0.00009</td>
<td>11,111</td>
</tr>
<tr>
<td>4. Larval survivorship</td>
<td>+ 100</td>
<td>0.00009</td>
<td>11,111</td>
</tr>
<tr>
<td>All four processes above</td>
<td></td>
<td>0.00267</td>
<td>375</td>
</tr>
<tr>
<td>5. Population estimate</td>
<td>+ 100</td>
<td>0.00008</td>
<td>12,500</td>
</tr>
<tr>
<td>6. Fruit misdirection</td>
<td>+ 500</td>
<td>0.00043</td>
<td>2,326</td>
</tr>
</tbody>
</table>

4.2.3. Limited fruit distribution
Increasing the likelihood of cherries to be sent to an endangered area by 100 percent increased $p$(annual mating pair) to 0.00009. Consequently, as with the bait spraying test, mean $Y_{MP}$ was only 11,111 years, and the 5th percentile equaled 570 years. Increasing this likelihood by 500 percent caused a significant increase in $p$(annual mating pair) to 0.00043. This gave mean $Y_{MP}$ of 2,326 yr, and the 5th percentile equaled 120 years.

4.2.4. Larval survivorship to adulthood
A 100 percent increase in survivorship of larvae to adults increased $p$(annual mating pair) to 0.00009, and, as before, mean $Y_{MP}$ was 11,111 yr, and the 5th percentile was 570 years.2

4.2.5. Combination of all four processes
The combination of parameter changes in all four processes at once obviously had the greatest impact on model predictions. In that case, $p$(annual mating pair) was 133.5 times greater than the baseline value: 0.00267 versus 0.00002. This gave mean $Y_{MP}$ of 375 yr, while the 5th percentile equaled 20 years. Arguably, these results might still indicate the systems approach is acceptable, given that a couple of decades should elapse before a mating pair occurred. Regardless, the fact that 100 percent changes to three processes and a 50 percent change to one were needed to begin to suggest a threat from ECFF via this pathway is good support for safeguarding level provided by the proposed systems approach.

4.3. Scenario 2 systems approach results

4.3.1. Trap density = 5 per square mile
The mean number of mated female flies within 200 m of the detection was 199 (max = 1,644), and mean eggs oviposited after bait spraying was 850 (max = 10,047). This increase over the

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2 Note that it was completely coincidental that the impacts of these three different sensitivity tests gave values for $p$(annual mating pair) that were equal to each other.
totals in Scenario 1 indicate the significance of being outside a quarantine area with lower trap densities. Outside the 200 m area the mean number of mated females was 19 (max = 168), and the mean realized number of eggs laid was 80 (max = 1,013).

The value for $p$(annual mating pair) was 0.00365 inside 200 m, and mean years to the first mating pair at an endangered area, $Y_{MP}$, was only 244 yr, with a 5 percent chance of that happening within 13 yr (Fig. 9A).

**Figure 9.** Cumulative probability for the years to first mating pair of European cherry fruit flies at an endangered area via cherries from the quarantine area in New York state for Scenario 2 for either A) five traps or B) two traps per square mile. The red arrow indicates the mean of the distribution, and the labeled dashed lines indicate the 5th (lower) and 95th percentiles.
4.3.2. Trap density = 2 per square mile
The mean number of mated female flies within 200 m of the detection was 495 (max = 4,609), and mean eggs oviposited after bait spraying was 2,119 (max = 26,396). This increase over the totals in Scenario 1 indicate the significance of being outside a quarantine area with lower trap densities. Outside the 200 m area the mean number of mated females was 46 (max = 458), and the mean realized number of eggs laid was 199 (max = 2,791).

The value for $p$(annual mating pair) was 0.0192 (1.9 percent) inside 200 m, and $Y_{MP}$ was 53 yr, with a 5 percent chance of that happening within 3 yr (Fig. 9B).

4.3.3. Summary
With the much larger populations compared to Scenario 1, one or more mating pairs of ECFF in endangered areas occurred much more often in Scenario 2. Still, Scenario 2 still seems to meet the expectations for safeguarding the risk from ECFF on this fruit, especially for the 5 traps per square mile density protocol.

5. Conclusions

In Scenario 1, the risk of ECFF spreading to new at-risk areas in the United States via cherries from quarantine areas of New York State was negligible provided the proposed systems approach is followed. This means only shipping fruit from orchards with zero ECFF detections during regulatory trapping before harvest, bait spraying according to the pest response guidelines, and limiting fruit distribution to non-cherry-producing areas as identified by the Agency.

Model sensitivity analyses indicated that those predictions were sufficiently robust to potential specification errors, especially as related to the following four processes: 1) the starting population size estimate, 2) efficacy of bait spraying, 3) the likelihood of fruit to be misdirected to an endangered area, and 4) larval survivorship to adulthood. Unless each of those processes had error rates of 100 percent or more (+/−, depending), model predictions should adequately characterize the risks of establishment of ECFF via this pathway.

In Scenario 2 (new quarantines from detections in 2018), the lower trapping densities at those locales meant that the risk was no longer negligible, because ECFF population sizes are likely to be much greater. But despite values of $p$(annual mating pair) that were much closer to or slightly greater than 1 percent, the systems approach still seemed to provide sufficient safeguarding, although less robust to model specification errors.

6. Literature Cited


