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Updated Modeling for Evaluating Systems Approaches for Mitigating the Risk of European Cherry Fruit Fly, *Rhagoletis cerasi* (L.), in New York State Cherry Fruit Under Quarantine

Probabilistic Model Descriptions

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EXECUTIVE SUMMARY

The presence of European cherry fruit fly (ECFF), *Rhagoletis cerasi* (L.), in New York State has resulted in a large area being quarantined since 2017. As a host of ECFF, cherry (principally *P. avium* L.) fruit produced in quarantine areas in New York State pose a risk to cherry-producing areas where fruit could be distributed. We evaluated systems approaches designed to mitigate the pest risk enough to allow safe movement of quarantine fruit to non-endangered areas. In 2018, we used a probabilistic model to evaluate the effectiveness of a systems approach at mitigating the risk of establishment of ECFF in new areas, to allow for limited movement of cherries from the quarantine area. The following three independent mitigation measures were the components of the tested systems approaches:

- Low pest prevalence, as determined by regulatory trapping
- Certified insecticide spraying, to kill flies
- Limiting distribution of fruit to areas with no commercial cherry production

Now, ECFF can be considered to have established in New York State, which brings into question low pest prevalence status. The simulation models depend on estimates of ECFF population sizes as a function of trap density, and our approach is unchanged from before. However, new data suggest the previous bait spray chemical, GF-120, is not effective on ECFF, and no replacements have been named yet. Therefore, we have modified the model to account generically for insecticide spraying.

The modeling objective was to identify—at the trap densities in use and for the associated population sizes—the minimum spray efficacy rate [i.e., *p*(surviving spray)] required to adequately mitigate the risk of ECFF moving to an endangered area in fruit from New York State. Certified sprays that meet or exceed the required efficacy levels will be determined by program managers, so far as possible. We evaluated systems approaches for two kinds of areas: those with verified ECFF captures within 10 miles (higher risk), and those at least 10 miles away from the nearest ECFF capture (lower risk).

For higher risk production areas, minimum *p*(surviving spray) values meeting our risk mitigation standard varied from 0.29 [i.e., 71 percent mortality] at 100 traps per mi^2, to 0.03 [97 percent] at 5 traps per mi^2. The value at 10 traps per mi^2 was 0.04, that at 25 traps per mi^2 was 0.13, and that at 50 traps per mi^2 was 0.20. The required efficacy rate will therefore be the easiest to achieve—but still perhaps challenging—for areas covered by a density of 100 traps per mi^2.

For lower risk production areas, the systems approach would involve the same independent measures as above except that only the lowest trap density (5 per mi^2) would be required, provided they meet an additional requirement for weekly “float tests” (or other means) for larvae in fruit beginning at harvest. This is not technically a mitigation measure, but provides additional evidence that a cryptic population of ECFF is not present. In that case, any chemical(s) certified for higher risk areas under a trap density of 100 traps per mi^2 would be very adequate. If such certification is not possible, then the lower population estimates valid for these areas justify an alternative minimum efficacy rate of 48 percent mortality.

1. Introduction

1.1. Purpose and Scope

The objective of this report is to update and document the probabilistic models and simulation results 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 (principally *P. avium* L.) from domestic quarantines in New York State. ECFF was first detected in New York in 2017 (Barringer, 2018), and trap captures of flies have approximately doubled from 2018 to 2019 (PPQ and NYSDAM, 2019). As a host of ECFF, cherry fruit produced in quarantine areas in New York State pose a risk to cherry-producing areas where fresh fruit may be distributed. The systems approach would allow for limited fruit distribution from the quarantine area to non-cherry producing areas as identified by the Agency. The first versions of the systems approach were evaluated before the 2018 growing season (PPQ, 2018b). This report represents an update to the current situation, and the inclusion of new information on ECFF ecology, solely to provide technical justification for the program. The results support the adoption of some options for the upcoming growing season, but some of the rationale for the measures chosen, as well as any consideration of operational issues or limitations, are beyond the scope of this technical report. Those are addressed in a separate document.

1.2. Mitigations considered

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

- **Confirmation of Area of Low Pest Prevalence**, as determined by regulatory trapping. Following the confirmation of a detected specimen as ECFF, regulatory 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: 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, 2018a).
- **Insecticide spraying**, to kill flies.
  The fruit fly quarantine area covering a 4.5 mile radius around all positive fruit fly sites will be treated with a specified chemical that is yet to be determined. The previous systems approach required the use of GF-120 (Spinosad), but we do not have direct evidence that it is efficacious against ECFF. Some tests have shown promise against related species (e.g., *R. indifferens* Curran [Western cherry fruit fly], in Yee, 2008), but others have not (PPQ, personal communication). Therefore, we took the approach here of modeling efficacy as a generic effect (see below) to determine a minimum level that provides sufficient risk mitigation. The program managers will work with cooperators to specify which chemical(s) meets that threshold.
- **Limiting distribution of fruit to areas with no commercial cherry production**, to stop infested fruit from getting to hosts in other endangered areas.
  The restricted areas are defined by the Agency. For 2018, fruit could not be shipped to the following places (APHIS, 2018): California; Michigan; Oregon; Washington; and the

New York counties of Chautauqua, Columbia, Dutchess, Delaware, Niagara (outside the quarantined area), Orleans, Oswego Schuyler, Seneca, Tompkins, Ulster and Wayne; and the Pennsylvania counties of Adams, Erie, York and Lancaster.

1.3. Risk model overview

The model estimates various state variables and parameters. Chronologically, it estimates the total number of adults in the quarantine fruit area on day one, the total number of mated females, the number of mated females surviving insecticide spray(s) and natural mortality (separately, and in that order) by week, the total number of days of oviposition over all weeks, the total number of eggs laid, the total number of viable larvae from hatched eggs, the likelihood of infested fruit being misdirected to a commercial cherry producing area (endangered area), and the total number of larvae from those fruit that survive to adulthood (Fig. 1). The model result (output) of interest was the likelihood of getting one or more mating pairs of ECFF from misdirected infested fruit. That probability was then used to estimate the number of years to the first occurrence of a mating pair at an endangered area.

1.4. Scenarios considered

A critical difference in the situation now versus 2017-2018 is that ECFF populations are no longer adventive; they have effectively naturalized in New York State and begun dispersing inland, away from the border with Canada (PPQ and NYSDAM, 2019). This makes it more difficult to confirm the area of low pest prevalence measure. Therefore, we evaluated the effectiveness of the systems approach across different trap densities. At greater trap densities, with zero ECFF captures (or one, at most), we can be more certain that the population is smaller. Thus, the estimated fly population sizes are greatest at 5 traps per mi^2, and least at 100 traps per mi^2.

Detections of ECFF in traps in New York State in 2018 were widespread but still somewhat patchy (PPQ and NYSDAM, 2019). Thus, the first distinction we needed to make was between production areas in proximity to ECFF captures, and those still some distance from captures.

1.4.1. Higher risk production areas

The highest risk production areas are those with nearby ECFF captures, and our quantitative analysis focused first on those areas. Analyses have indicated that the mean annual natural dispersal distance for ECFF is about 8 miles (13 km) (PERAL, 2019). Adding 25 percent of that distance as a buffer, we defined the highest risk areas to be those within 10 miles of a capture, and lower risk areas as those 10 miles or more from a capture.

Many areas may only be covered by the lowest density of regulatory trapping (5 traps per mi^2). Regardless of trap density, we presume that ECFF have been captured since 2017 within 10 miles of these production areas, but that zero captures, or one capture, at most have occurred within the production area itself. As discussed above, our modeling objective was to determine the required spray efficacy to achieve a desired level of risk mitigation at the relevant trap density.

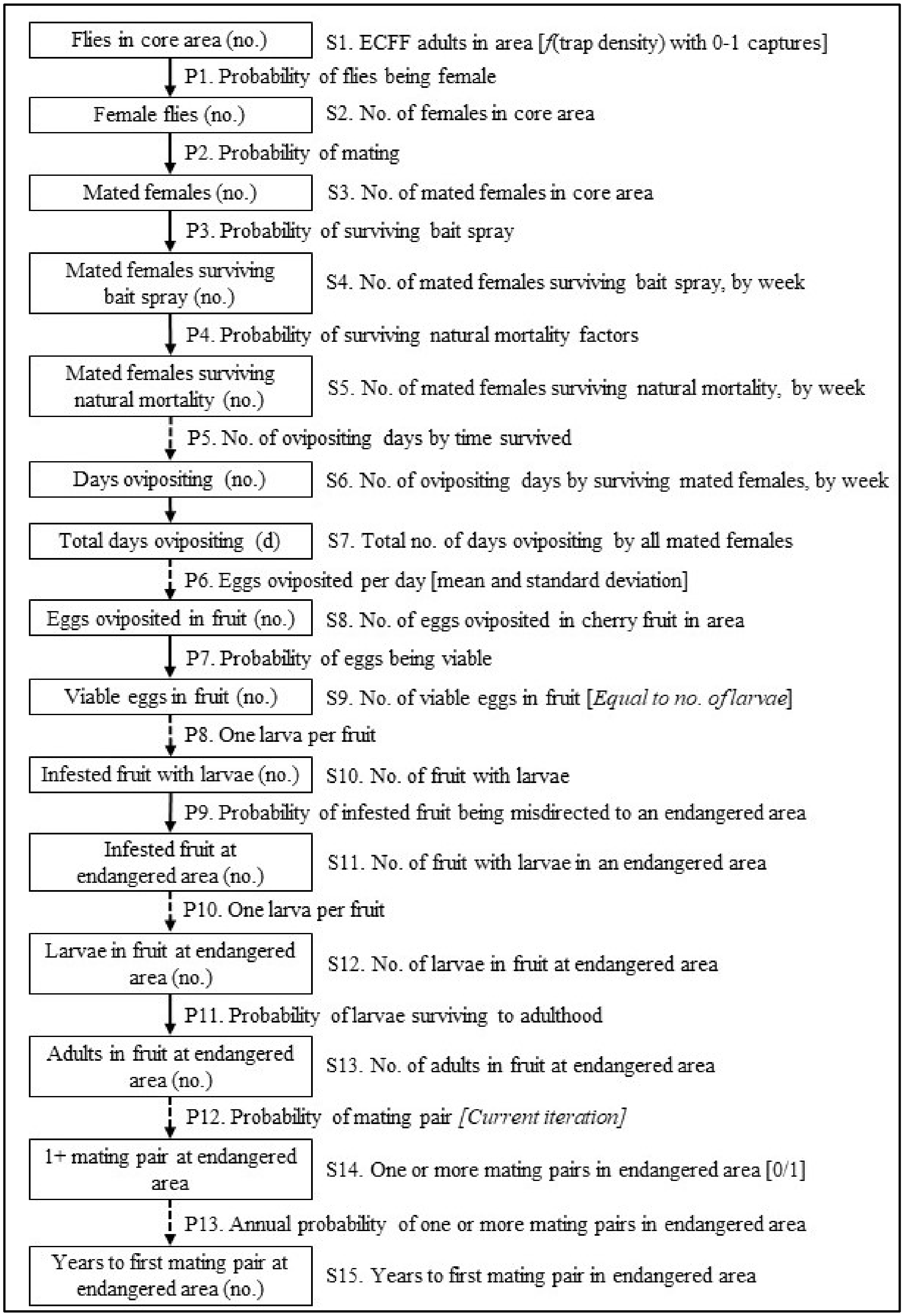

Figure 1. Diagram of the quantitative model for evaluating a systems approach for safe movement of cherries from New York that may be infested by ECFF. Rectangles are state variables, solid lines represent material transfer (same units, e.g., no. individuals), dashed lines information transfer (unit conversions), and transitions are probabilities or parameters.

The modeled scenarios for all trap densities in use, with the exception of 20 traps per mi^2, because that value has no easily mapped square. Thus, we created population size estimates for the densities of 5, 10 (9), 25, 40 (49), and 100 traps per mi^2. The most-used trap density in the regulated area is likely 5 traps per mi^2 rate [that density was modeled exactly as 5 rather than 4], but will have the greatest estimated ECFF population sizes.

In all cases, we increased values of spray efficacy—represented in the model as the likelihood of surviving the spray—incrementally (to the nearest one percent) until the 5th percentile for years to the first mating pair at an endangered area reached or exceeded 10 years.

1.4.2. Lower risk production areas

From above, lower risk areas are those that are 10 more miles away from the nearest ECFF capture. These regulated production areas are still subject to trapping at least at the 5 traps per mi^2 density (with zero detections, obviously) (PPQ and NYSDAM, 2019), and may therefore still be very low pest prevalence. In those cases, we think the trap density restriction might be waived, provided that all other systems approach measures are followed, and a separate pre-harvest (and weekly) confirmatory test is added. One such test of apparent interest is a “float” test (e.g., Yee, 2014) which looks for the presence of larvae in crushed fruit samples. An inspection based on a float test (or other valid method) would alleviate remaining uncertainties about the possible presence of a cryptic population of ECFF that had not been detected, because of a low density of poor traps.

The two modeling objectives for the lower risk areas were as follows:

1) Determine the risk associated with using the minimum required spray efficacy from above
2) For the lower population size estimate used for these areas (see below), determine the minimum required spray efficacy.

The first objective tests the impact of using the same certified spray program in these areas that was specified for higher risk areas. The expectation is that safeguarding would improve, since the population sizes are smaller. The second objective is aimed at determining how much the required spray efficacy could decrease, again because of smaller ECFF population sizes.

Population size estimate. If ECFF has not yet established in or spread to an area, then the population size is zero. However, we cannot simulate anything with that value. Therefore, we used a population size estimate based on the required in-grove trap density in New York, which is 2 traps per acre in, or the equivalent of 256 traps per mi^2. This results in a smaller population size estimate than for the 100 traps per mi density, which is sufficient for our purposes. It still overestimates the number of flies in any area with truly no ECFF population, but is justifiable programmatically, can be quantified exactly as we did above, and provides an amount of uncertainty to the simulation that is very similar to the earlier distributions.

Fruit inspections via float test. “Float” tests of fruit are commonly required by some entities to allow movement (e.g., Standardization Committee, 2017). Sampling procedures are beyond the scope of this report, but the program personnel would generally specify how to take samples, process them, prepare the float solution, carry out the examination, and report the results for certification.

For use in the ECFF systems approach, timing is the important factor. We recommend inspecting fruit at first harvest, and then once a week thereafter until the harvest is complete. Detection of one or more larvae (providing they are identified as or strongly suspected to be ECFF) would remove eligibility for movement under the systems approach.

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

In all cases below (including §2.3) we presented functions in standard @Risk format within Excel.

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):

$$s = \mathrm{RiskBinomial}(n,p) \qquad [1]$$

2.2.2. Beta distribution

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 (e.g., Bolstad, 2007):

$$p = \mathrm{RiskBeta}(\mathrm{a}_0 + \mathrm{a},\ \mathrm{b}_0 + \mathrm{b} - \mathrm{a}) \qquad [2]$$

where a_0 and b_0 are the prior values for a and b. Here we typically assumed a uniform prior, in which $\mathrm{a}_0 = \mathrm{b}_0 = 1$. 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:

$$X_{\mathrm{tot}} = \mathrm{RiskNormal}([N \times \mu],[(\sqrt{N}) \times \sigma]) \qquad [3]$$

where X_{tot} is the sum of interest, N is the variable entity, μ is the mean of the Normal distribution, and σ 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_{mp}) being present depends on how many adult pests survive (A_{surv}) in the shipment. If zero or 1 adults survive, the probability is zero. Otherwise, the probability is calculated as follows (PERAL, 2005):

$$p(\text{mating pair}) = 2^{A\text{surv-2}} / 2^{A\text{surv}} \qquad [4]$$

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., $p_{♀} = p_{♂} = 0.5$), only two possible combinations exist in which no potential mating pair is possible: when either all adults are males or all adults are females. Therefore, p(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(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_{ann}, estimates the annual probability of a mating pair being present.

2.3.4. Years to first mating pair

We use p_{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:

$$Y = 1 + \text{RiskNegbin}(1, p_{\text{ann}}) \qquad [5]$$

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

3. Model specifications

3.1. Overview

The general modeling objective was to determine the minimum required insecticide spray efficacy rate which should ensure a negligible risk of ECFF moving in fruit from New York State to an endangered area. Consequently, we simulated incremental increases in spray efficacy, represented in the model as p(surviving spray). This was done to the nearest one percent (0.01). We have assumed that the production area of interest is a cherry grove with ample fruit production, and covered by regulatory trapping at a particular trap density. The model starts with a prediction of the number of adults per week in the quarantine fruit area and ends with the probability of getting a mating pair from infested fruit at the endangered area (Fig. 1). We summarize below the parameter values and functions used, as appropriate (Table 1).

Table 1. State variables and parameters in the model of the systems approach for Scenario 1, for fruit from quarantine core areas.

Item	Description	Function	Parameters	Source
1	Adult flies in area, N_A (no.)	Histogram (Eqn. 6)	x_{Min}; x_{Max}; p values for each bin (see Fig. 2A-F)	Separate simulations (see §3.3) for each trap density, based on results using Manoukis et al., 2014)
1a	Adult flies remaining in area (no.)	*Assumption*	No net departure of flies from the area (entry and exit rates are equal)	Relatively low mobility of ECFF around hosts (Fletcher, 1989; Lux et al., 2016)
2	Female adults in area, $N_{♀}$ (no.)	Binomial (Eqn. 1)	$n = N_A$ p(female) = 0.5	e.g., Lux et al., 2016
3	Mated females, $N_{♀M}$ (no.)	*Assumption*	$n = N_{♀}$ p(mated) = 1	Note: 119/128 mated females captured (Katsoyannos et al., 2000)
4	Mated females surviving insecticide spray, by week, N_{BS} (no.)	Binomial (Eqn. 1)	$n = N_{♀M}$ p(surviving spray) = 0.01-0.99 (theoretically)	N/A (Not applicable)
5	Mated females surviving natural mortality, by week, N_{NM} (no.)	Binomial (Eqn. 1)	n = no. females surviving spray p(natural survival) = 1 − p(natural mortality) p(natural mortality) = 0.083 (8-20d); 0.209 (21-30d); 0.103 (31-40d); 0.040 (41-45d)	Moraiti et al., 2012
6	Ovipositing days by mated females, by week, D_S (d)	Discrete (≤40 flies); Central limit theorem (>40 flies; Eqn. 3)	Total days = 38 (days 8-45) n = no. surviving mated females Mean days per week (uniform p) = 4, standard deviation = 2	Moraiti et al., 2012 (biology)
7	Total ovipositing days, D_{Tot} (no.)	Arithmetic	N/A	N/A
8	Total eggs oviposited in fruit, N_{ovi} (no.)	Central limit theorem (Eqn. 3)	N = total ovipositing days Eggs per day per female: mean (μ_{egg}) = 5.085, standard deviation (σ_{egg}) = 0.676	Moraiti et al., 2012
9	Viable eggs [larvae] in fruit, N_L (no.)	$N_L = N_{ovi} \times$ p(hatch); rounded to nearest integer	Beta distribution for p(hatch): s = 11,310, n = 12,326; $\alpha_0 = \beta_0 = 0.5$ [Mean = 0.918; 5th percentile = 0.913; 95th percentile = 0.922]	Prokopy and Boller, 1970

Item	Description	Function	Parameters	Source
10	Fruit with larvae, F_L (no.)	$F_L = N_L \times F{:}L$	One fruit per larva; $F{:}L$ = 1:1 = 1	Fletcher, 1989
11	Fruit with larvae misdirected to endangered area, F_{EA} (no.)	Binomial (Eqn. 1)	$n = F_L$ p(misdirection) = 0.00116	PPQ, 2001
12	Larvae in fruit at endangered area, N_{EA} (no.)	$N_{EA} = F_{EA} \times L{:}F$	One larva per fruit; $L{:}F$ = 1:1 = 1	Fletcher, 1989
13	Larvae surviving to adulthood, N_A (no.)	Binomial (Eqn. 1)	$n = N_{EA}$ p(larval survival) = Pert distribution with minimum = 0.021, most likely = 0.084, and maximum = 0.206 [mean = 0.0939; 5th percentile = 0.0417; 95th percentile = 0.154]	Boller and Remund, 1989
14	One or more mating pair formed (1,0)	Binomial (Eqn. 1)	$n = 1$ p(mating pair) = Eqn. 4	PERAL, 2005
15	Years to first mating pair (no.)	Negative binomial (Eqn. 5)	p = annual likelihood of mating pair [mean of item #14]	Vose, 2000

We simulated weekly intervals of potential reproduction rates by ECFF beginning on day 8, when oviposition could start, and ending on day 45 (Moraiti et al., 2012). Thus, Week 1 corresponded to days 8 to 14, Week 2 was days 15 to 21, and so on, except that 'Week 5' only included days 43 to 45.

3.2. Defining a risk threshold for systems approach evaluation

Normally we would have a well-defined distribution for insecticide spray efficacy for the given chemical(s), based upon empirical evidence. Using that distribution, model outcomes would indicate whether or not the risk was effectively mitigated, based on the annual probability of a mating pair in an endangered area, and the associated estimate of the number of years to that occurring.

However, at present we have no agreed-upon chemical, and no empirical data, and are therefore modeling a generic efficacy rate for a required chemical. Accordingly, we need to define a standard for acceptable risk mitigation, but no exact or agreed-upon standard exists for determining such a threshold.

Our idea was to set a standard based on ensuring that movement of quarantined fruit in the ECFF systems approach was much less likely to cause establishment in an endangered area than natural spread of ECFF. Thus, we examined the record of spread of ECFF from Canada to New York, and consulted an analysis of potential natural spread to a key endangered area, Michigan. ECFF was first detected in Ontario in 2015, and then in New York State on the border in 2017

(PERAL, 2019). That distance (by land around Lake Ontario) is approximately 200 km, which means ECFF dispersed an average of about 100 km annually (or 8 km monthly) to reach New York. Based on all available information for ECFF, scientists estimated its mean annual spread distance to be 13 km, which implies it could reach Michigan naturally by 2036 (PERAL, 2019). However, if it moved faster—at a maximum possible rate of 40 km annually—it could reach Michigan by 2025.

For the choice of a threshold time period, then, we used ten years, or the approximate average of the two estimated establishment dates. Consequently, our standard was as follows:

- The systems approach should give no more than a five percent chance of a mating pair occurring at an endangered area within ten years

In other words, an approach that gave a five percent chance in nine years would not be acceptable, and neither would a system that gave a six percent chance within ten years. In this range, a viable systems approach should give a value of approximately 200 years as the mean time to a mating pair in a misdirected fruit. This corresponds to an annual probability of about 0.0050.

Overall, then, while ECFF may reach Michigan via natural spread within about 16 years on average, the systems approaches we have specified should ensure that establishment via this pathway to *any endangered area in the United States* would take at least 200 years on average (PERAL, 2019).

3.3. Estimating initial population sizes

The starting point of the model is an initial estimate of the number of flies in the area. This prediction is critical because low pest prevalence in the area is a keystone independent measure in the systems approach, and because ECFF can now be considered naturalized in the area (above). Model estimates of ECFF population densities depend explicitly on the trap density in the area under consideration. Areas with only 5 traps per mi^2 yield the greatest population estimates, because the likelihood of capturing flies is very low. Mean population size estimates decrease with increasing trap densities, so areas with 100 traps per mi^2 have the smallest mean size estimates and the smallest uncertainties (i.e., minimal range of possible values).

We estimated the number of adult flies in the core area using results from TrapGrid, a trapping network simulation model (Manoukis et al., 2014) parameterized for the different densities and trap attractiveness (a constant). The outputs from TrapGrid are estimated daily likelihoods of a fly population escaping capture. The standard trap for ECFF is a yellow panel trap ("protein-baited yellow sticky card with a lure of ammonium acetate in a polycon dispenser"; PPQ, 2018a). Based on reports from various researchers (e.g., Lux et al., 2016), we estimated trap attractiveness to be 0.27, which represents very low attractiveness.

For each trap density, we determined mean *p*(capture) at day 1 using TrapGrid with 200 flies, the diffusion coefficient, *D*, equal to 10,000 (), and random distribution of flies around the grid at start. As trap density rises, so does *p*(capture). The trap densities modeled were 5, 10 (9), 25, 50 (49), 100, and 256 (see §1.4.2). The only trap density in use in the regulated areas in New York

State that we did not model was 20 traps per mi^2, because the grid was challenging to create (20 is not a square, and there is no approximate square close to 20).

We used the different mean p(capture) values in a separate simulation model (details available upon request), with 100,000 iterations, which tested each fly successively in a binomial process (Eqn. 1) with $n = 1$ and p(capture) until a fly is caught ($s = 1$). That value minus one estimates the maximum number of flies present that would **not** give a detection. We summarized the simulated results in a histogram for the main model, as follows:

$$N_A = \text{RiskHistogrm}(x_{Min}, x_{Max}, [p \text{ values}]) \qquad [6]$$

where N_A is the number of adults, x_{Min} is the minimum, x_{Max} is the maximum, and the p values indicate the likelihoods for each interval between the minimum and maximum.[1]

Mean p(capture) values and resulting population estimates across six selected densities were presented visually (Fig. 2). The mean population size at 5 traps per mi^2 (Fig. 2A) is nearly fifteen times greater than that at 100 traps per mi^2 (Fig. 2E). Because of binning in the histograms specified for the system approach model, predicted means were a little smaller than the results from the capture model.

To highlight the apparent poor performance of low trap densities with ECFF in this situation, after 29 days of trapping at 5 traps per mi^2 the mean p(capture) increased to only 0.7 percent (0.007).[2] That was over 21 times greater than the value at day 1, but demonstrates that detections could be rare at that density even over the entirety of the harvest season. By comparison, mean p(capture) at day 29 with 100 traps per mi was 8.7 percent; that value is not ideal, but is a great improvement over the likelihood with 5 traps per mi^2.

Ideally, no ECFF have been captured in the fruit-growing area prior to harvest. Because we estimated the maximum population size with no detections, though, the model results are also acceptable if one fly has been captured. Capturing two flies, however, would clearly imply a population size about twice what we estimated here, meaning the situation no longer meets the requirements of the systems approach.

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[1] In @Risk, the function used is spelled as shown: 'RiskHistogrm'

[2] 1000 simulations. Otherwise model specifications were as reported.

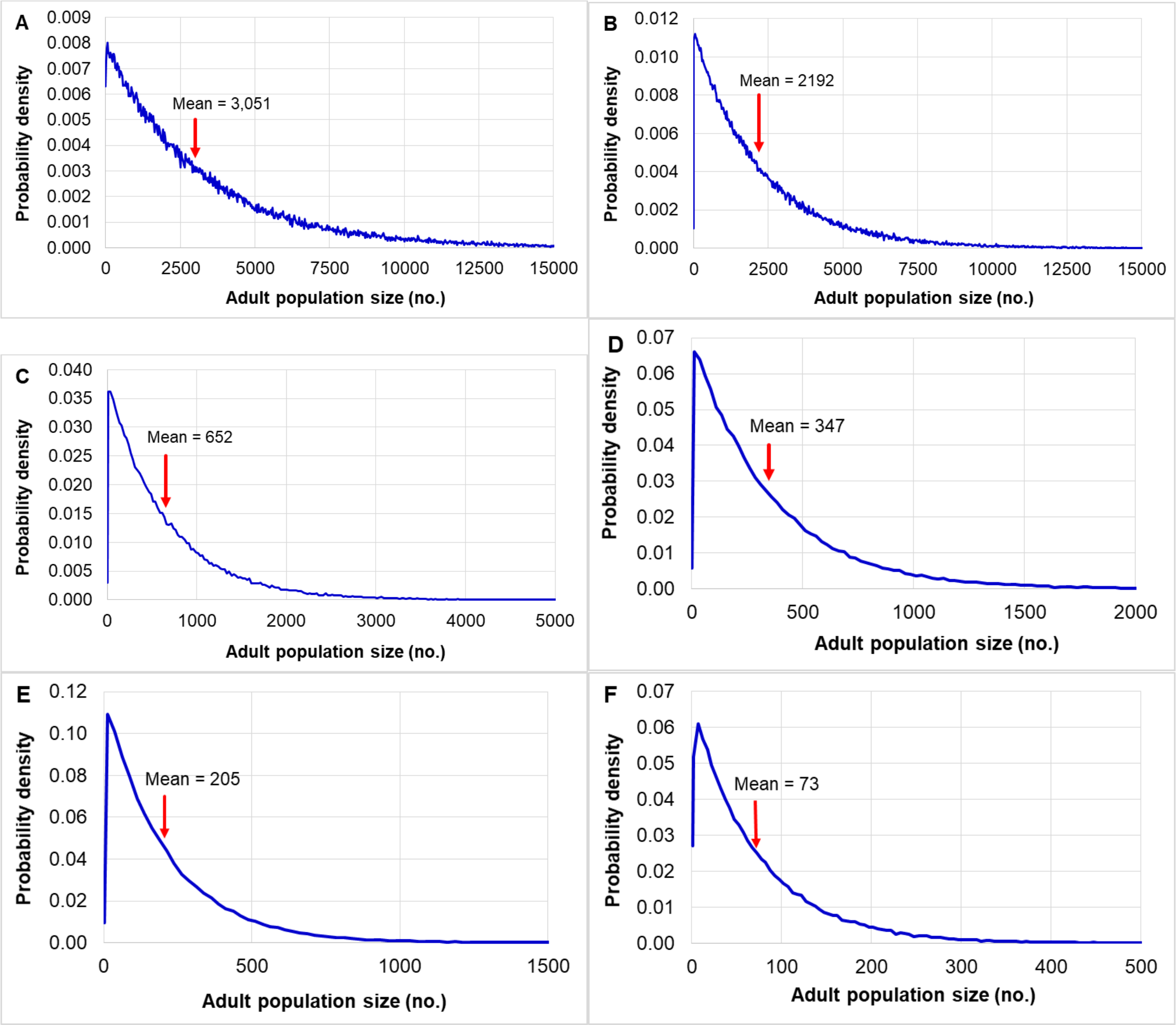

Figure 2. Probabilities for the number of adult European cherry fruit flies in the field when the trap density is (A) 5 traps per mi^2, (B) 9 traps per mi^2, (C) 25 traps per mi^2, (D) 49 traps per mi^2, (E) 100 traps per mi^2, and (F) 256 traps per mi^2. Red arrows indicate means.

3.4. Modeling methodologies for state variables

Several of the state variables in the updated model are calculated exactly as they were previously (PPQ, 2018b). We note where this is true.

3.4.1. Females in the area

This was unchanged in this version. We predicted the number of males and females based on an equal sex ratio (i.e., p(female) = 0.5) (e.g., Lux et al., 2016). The number of females, $N_♀$, was a binomial (Eqn. 1).

3.4.2. Females in the area after dispersal

This was unchanged in this version. This species tends 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 very few flies will move in **or** out of the core area, and that the number will be equal. Lux et al. (2016) made the same assumption in their model.

3.4.3. Mated females

This was unchanged in this version. We have some evidence that the likelihood of mating in wild ECFF may be over 90 percent (Katsoyannos et al., 2000), but made the assumption that any mature females in the area would be mated.

3.4.4. Females surviving spraying

In spraying, flies (male and female) are contacted by an insecticide, resulting in their death.

The preferred chemical against ECFF in the previous version of the systems approach was a bait spray, GF-120, which was ingested by the flies (PPQ, personal communication). Unfortunately there is a lack of direct efficacy data for GF-120 on ECFF. We found a published report for the effects of GF-120 on a related species, *Rhagoletis indifferens* Curran (Western cherry fruit fly) (Yee, 2008), with mean efficacy of about 0.82 (or a 0.18 survival rate). However, in other trials on congeners GF-120 has seemingly performed very poorly (PPQ, personal communication).

Consequently, for the insecticide spray measure in this systems approach analysis we could not work with data for a particular chemical. Instead, the program managers will work with state officials to agree on likely useful options. Other chemicals are commonly used for the control of cherry fruit fly (*R. cingulata*), spotted wing Drosophila (*Drosophila suzukii*), and other pests (e.g., Agnello et al., 2019; Demchak et al., 2012), and some of these may be effective for ECFF.

For the model, we adopted a generic approach in which we determined acceptable mortality rates provided by unspecified insecticide sprays. As mentioned above, this was done by finding the minimum value of p(spray survival) [1-percent increments] that gave a 5th percentile of 10 or more years for the time to the first mating pair at the endangered area. Otherwise, calculation was done as in the previous model. The number of mated females surviving spray each week (i), $N_{\mathrm{BS},g,i}$, was calculated in a binomial process (Eqn. 1) with $p = p$(surviving spray). The value of n varied from week to week, and survival was also calculated for days 1-7 in the model (the period prior to maturity). That week (Week 0, effectively) n was equal to $N_{♀}$, while in every week thereafter it was $N_{\mathrm{NM},i-1}$, the number of mated females that had survived both insecticide spraying and natural mortality the previous week (see §3.2.5).

3.4.5. Females surviving natural mortality

This was unchanged in this version. From emergence to the end of oviposition, some female flies may die of natural causes. We estimated survival probabilities for four time periods from the start of oviposition on day 8 to the end of oviposition on day 45 (Table 2) from Moraiti et al. (2012). Very little mortality occurs before day 8. Values were digitally interpolated from Fig. 3 (‘Allopatric populations,’ Stecklenburg strain) in Moraiti et al. (2012).

In the model, mated females surviving natural mortality per week, $N_{\mathrm{NM},i}$, is a binomial process (Eqn. 1) with p(natural survival) applied to the appropriate week as in Table 2 (e.g., p for week 2

[15-21 d] = p(natural survival) @8-20d). The value of n was $N_{\mathrm{BS},i}$ for the current week. Note that $N_{\mathrm{NM},i}$ is the number of mated females surviving both hazards each week.

Table 2. Probabilities for natural mortality of European cherry fruit flies over different time spans (Moraiti et al., 2012).

Time span (start-end days)	p(natural survival)
8-20	0.917
21-30	0.791
31-40	0.897
41-45	0.960

3.4.6. Total ovipositing days

This was unchanged in this version. For each week, the total ovipositing days by mated females depended on surviving and non-surviving mated females. The number of days per week from surviving mated females ($D_{\mathrm{S},i}$) was simply the product of 7 and $N_{\mathrm{NM},i}$.

The number of ovipositing days per week by non-surviving mated females ($D_{\mathrm{NS},i}$) depended on how many there were each week, and on how long they survived—from 1 up to 7 days. If the number of flies that week was greater than 40, we used the central limit theorem (Eqn. 3). The mean number of days was 4.0, and the standard deviation was 2.0—both results were based on a uniform distribution from 1 to 7. [Note that our calculations assume the fly oviposited on the day it died.]

If the number of non-surviving flies in a week was 40 or less, we predicted the number of days for individual flies. The total number of days each fly (y) lived in the period ($D_{\mathrm{NS},I,y}$) in which it died was a discrete function with equal probabilities for each day, as follows:

$$D_{\mathrm{NS},I,y} = \mathrm{RiskDiscrete}([d \text{ values}],[\text{weights}]) \qquad [7]$$

where d values are the array of days (1 to 7), and weights are all 1 (i.e., equal probabilities).

The total ovipositing days per week by all mated females was therefore:

$$D_{\mathrm{Tot},,i} = \Sigma(D_{\mathrm{NS},i,,1}, \ldots, D_{\mathrm{NS},i,y}) + (7 \times N_{\mathrm{NM},i}) \qquad [8]$$

where the sum over y is for the total ovipositing days each week from individuals. The sum over i (not shown) would be D_{Tot} over all weeks.

3.4.7. Total eggs laid

This was unchanged in this version (Table 1). We estimated the total potential eggs (N_{pot}) laid using the Central Limit Theorem (Eqn. 3) with parameters μ_{egg} and σ_{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.

3.4.8. Fruit with viable larvae

This was unchanged in this version. We estimated the probability of eggs to hatch, *p*(hatch), and presumably become larvae, as a beta distribution [Eqn. 2]. The number of fruit with viable larvae, N_L, was the product of *p*(hatch) and N_{ovi}, rounded *up* to the nearest integer.

3.4.9. Infested fruit misdirected from distribution area

This was unchanged in this version. We used a binomial process to increase the chance of multiple infested fruit being misdirected, despite the resulting increase in uncertainty. We based our likelihood estimate on data collected several years ago on avocados from Mexico. Those 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. Recall that any cherry-producing areas are likely to have negligible demand for cherries from elsewhere, which should significantly limit the potential for infested fruit to move to such places.

3.4.10. Fruit with larvae surviving to adulthood

This was unchanged in this version. Data on total mortality from larvae to adulthood were from Boller and Remund (1989). The outcome of our estimation was a Pert (skewed) distribution, with mean = 0.053 (Table 1).

3.4.11. Mating pairs and years to first mating pair

This was unchanged in this version. The probability of a mating pair (Eqn. 2) depended directly on the number of surviving adults in the endangered area, assuming they had all arrived together in the same shipment and stayed in proximity to each other. That value was used to determine if a mating pair resulted, from 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).

4. Results and Discussion

4.1. Higher risk production areas

4.1.1. Required spray rates

These are production areas for which ECFF have been captured within 10 miles. Relatively high spray efficacy rates were required for all five different tested trap densities (Table 3). We knew the required mortality rate would be lowest at for areas under 100 traps per mi^2, but the result of 0.71 still seems relatively high, and it may be challenging for managers to certify a chemical or combination of chemicals that meet that threshold. At the other end, with either 5 or 10 traps per mi, the required mortality rates are so large—96 or 97 percent—that meeting that threshold is likely not possible.

Table 3. Model results for higher risk cherry production areas in New York State showing the ECFF spray survival rate and associated mortality rate required for each area trap density (no. per mi^2), as well as the likelihood of a misdirected mating pair, and the mean years to the first mating pair with 5th percentile.

Density	Required spray rates		Mating pair	Years to first mating pair in endangered area	
	Survival	Mortality	likelihood	Mean	5th Percentile
5	0.03	0.97	0.00434	230	12
10	0.04	0.96	0.00442	226	12
25	0.13	0.87	0.00567	176	10
50	0.20	0.80	0.00514	195	10
100	0.29	0.71	0.00543	184	10

4.1.2. Supplemental results

The model also provides results about the levels of activity of ECFF in each scenario, which may be of some interest. In general, the systems approach operates by reducing the number of mated females in the area, with subsequent effects on the number of days they oviposit and the number of eggs laid (Table 4). Increasing spray efficacy offsets increased population size estimates as one moves from 100 to 5 traps per mi, creating approximately equivalent results for mated females, ovipositing days, and eggs laid. The results imply that the risk associated with any option in which the mean number of eggs laid increases much above 1,100 would be untenable. Spray efficacy requirements are therefore attuned to reducing the population size enough to give an average of only 30-44 mated females in the production area.

Table 4. Model results for higher risk cherry production areas in New York State showing the ECFF spray survival rate and associated mortality rate required for each area trap density (no. per mi^2), as well as the likelihood of a misdirected mating pair, and the mean years to the first mating pair with 5th percentile.

Density	Spray Survival Rate	Mated Females (no.)		Ovipositing Days	Eggs Laid (no.)	
		Mean	Max.	(no.)	Mean	Max.
5	0.03	45.8	293	192.7	980.1	6,772
10	0.04	44.3	420	189.6	964.0	9,818
25	0.13	43.8	526	219.1	1,114.2	13,198
50	0.20	36.9	384	208.5	1,060.0	11,761
100	0.29	33.0	353	219.2	1,114.7	11,949

4.2. Lower risk production areas

Recall that for lower risk areas the trap density can be the minimum of 5 traps per mi^2, except within orchards where it is 256 traps per mi^2. For these areas we made two determinations: 1) the risk associated with the use of a chemical meeting the efficacy standard from above, and 2) the minimum spray efficacy required for the minimal population sizes estimated specifically for this case (§1.4.2). The latter item might serve as a “last resort” systems approach for the lowest risk areas if the spray efficacy level(s) required for higher risk areas cannot be certified in 2020.

4.2.1. Risk with required spray efficacy for higher risk areas

At the density of 100 traps per mi^2, the required spray mortality rate was 0.71 or more [p(surviving spray) ≤ 0.29]. Using that value in the model with the lower population estimate from the use of 256 traps per mi^2, the annual probability of a mating pair in an endangered area decreased by 83 percent, to 0.00092 (Table 5). The mean number of years to that occurring was 1,087, with a 5 percent chance of happening within 56 years. As expected, this is significantly safer than for higher risk areas (Table 4).

4.2.2. Risk with minimized spray efficacy for lower risk areas

When we allowed p(surviving spray) to go above 0.29, we found that the minimum efficacy rate required for these areas was 0.52 (Table 5). In other words, the required mortality rate for the chemical was only 0.48, which should be easier to meet than the rates needed for higher risk areas.

Table 5. Model results at three selected probabilities of surviving insecticide sprays (see text) for the ECFF systems approach for lower risk production areas, showing the probabilities of a mating pair occurring in an endangered area, and the years (mean and 5th percentile) to the first such pair occurring.

***p*(surviving spray)**	***p*(mating pair)**	**Years to first misdirected mating pair**	
		Mean	**5th percentile**
0.29	0.00092	1,087	56
0.52	0.00557	180	10
0.53	0.00592	169	9

4.3. Modeling methodology caveats

For transparency, we thought it would be useful to point out some of the caveats that exist within the approach described here. We strive for realism and accuracy where possible, but sometimes it is also prudent to make simpler assumptions that may overestimate the risk somewhat. This should minimize the consequences of any unknown significant errors, if they occurred. For example, assuming that all surviving females will successfully mate is an assumption that will tend to overstate how many eggs are laid, but is worth making because we expect that proportion to be high anyway (some evidence supports that), and doing so simplifies the modeling explanation. Note that we would never knowingly *understate* a risk via an assumption.

Therefore, following are some known assumptions and caveats built into this analysis, and their possible impacts on the estimated risks.

- We used a population size of 200 in the TrapGrid model when determining the likelihood of capture at different trap densities. The model is not particularly sensitive to this value (Manoukis, personal communication), but will overestimate the capture rates for any situation in which population sizes are very low (i.e., near zero). This means population predictions in the mode—and associated risks—will be outsized for some real situations in the field. But adopting a general approach is justifiable to ensure the systems approach provides acceptable risk mitigation across all field conditions.
- When simulating for the population size estimate we are finding the *maximum* number of flies that gave zero detections; thus, this value is just 1 individual less than the population

size that would give 1 detection. This is the main reason we think capturing one fly in an area would not change the situation significantly, but capturing a second fly would.

- The assumption that every surviving female will be mated will increase the number of eggs being laid. Real data suggests that the true proportion may be, on average, more like 93 percent (Katsoyannos et al., 2000), but we do not know how well those conditions would match these.
- Available evidence suggests that ECFF oviposit only one egg per cherry fruit (Fletcher, 1989). Assuming this in the model maximizes the number of infested fruit available to be misdirected, which slightly overstates the real risk.
- We have assumed that the data on misdirection of avocados from Mexico is a good representation for cherries from New York. In this case, the data probably overstate the likelihood of misdirection somewhat, because consumers in endangered areas could not get locally-produced avocados. Local cherries are available to endangered area consumers in this case, which should minimize the likelihood of misdirection of New York fruit.
- When calculating the likelihood of getting a mating pair from infested fruit at the endangered area, we have assumed that all larvae are together in time and space. Fruit harvested from an infested grove could reasonably be grouped together, but is less likely over several weeks of harvesting, as represented in the model. Multiple destinations combined with random sorting of fruit would also reduce the likelihood of larvae clustering at an endangered area.
- The model results are probabilities of getting a mating pair at an endangered area, but several processes still have to occur after that for successful survival and establishment of the population (e.g., escaping into the environment, finding a host, surviving natural mortality). Modeling these processes would be challenging given the lack of relevant direct information for ECFF, and the large number of potential destinations involved. Minimizing the chance of getting a mating pair at the endangered area is more tractable, and leaves those remaining processes as an additional buffer against establishment.

5. Recommendations

The systems approach evaluated here for areas with nearby ECFF captures consisted of the following independent measures:

- Regulatory trapping with zero or at most one capture of ECFF in the fruit production area
- Certified spraying beginning at least 28 days before harvest and continuing weekly until harvest is complete, using a chemical verified by program managers as providing at least the minimum efficacy required, given the trap density covering the production area
- Limiting distribution of fruit to non-cherry producing areas

5.1. Higher risk production areas

Based on modeling results (Table 4), we recommend that fruit shipped from the quarantine area in New York for fresh market use **should only be from** production areas covered by the highest regulatory trapping density of 100 traps per mi^2, **provided that** the program managers validate that a particular certified spray will meet a **spray mortality rate ≥ 71 percent**. Lower densities could be stipulated if spray efficacies at rates of 80 percent or more can be certified (see Table 4), but that seems unlikely at present.

Deploying traps at the maximum density in the regulated area to cover relevant production areas could be challenging, in terms of the resources required for installation and monitoring. But it is necessary to mitigate the risk of ECFF spreading to other endangered areas in the United States via cherries from New York State.

5.2. Lower risk production areas

For production areas that are highly likely to be low pest prevalence, based on being 10 miles or more distant from any ECFF captures, we evaluated an option using all of the independent measures above, but in conjugation with a separate weekly pre-shipping 'float test.' The float test would help verify that a cryptic population of ECFF was not present in the production area, despite the regulatory trapping density being less than that required for the higher risk areas above. Thus, the designated production area in this scheme would meet all of the following in order for fruit to be eligible for fresh market use:

- Area is at least 10 miles from any verified ECFF captures (or a greater distance if deemed appropriate by program managers)
- Area is covered by regulatory trapping at a minimum of 5 traps per mi^2 with no detections
- Area subject to certified spraying beginning at least 28 days before harvest and continuing weekly until harvest is complete, using the same chemical(s) mandated by program managers for higher risk areas
- Weekly negative results from float tests, using test specifications mandated by the program managers and certified by relevant officials
- Limiting distribution of fruit to non-cherry producing areas

If no chemicals meet the required efficacy rate for higher risk areas (mortality = 0.71), then fruit from lower risk areas could still be marketed as fresh fruit if program managers can certify an insecticide spray to meet the efficacy rate of at least 0.48 [p(surviving spray) ≤ 0.52, Table 5].

5.3. Alternative for program non-eligible fruit

Fruit from production areas that are not eligible for fresh market sale using the systems approach, for whatever reason (e.g., insufficient trap density in the area), can still move for processing. Those guidelines are set out in a separate document (PPQ, 2019).

5.4. Possible areas for program improvement

Several things related to research or development could be considered to facilitate improved options in the future for systems approaches for ECFF on quarantined cherry fruit from New York.

One item already discussed by program managers is identifying and using better traps for ECFF. This would impact the program by providing better information about the true extent of ECFF in

New York, and perhaps better information on host use. It might also reduce the required trap densities, with associated benefits on the resources required for trapping and monitoring. Finally, it would improve our modeling evaluation by (presumably) reducing population size estimates and uncertainties. Better confirmation of low pest prevalence overall would mean less risk mitigation is needed from the other two measures, which could mean a reduction in the minimum efficacy required for insecticide sprays.

Another activity that we think would be useful is direct empirical testing and registration of insecticides for the control of ECFF. This would increase confidence in the mitigation levels provided by spraying in the program. From a modeling perspective, this would enable systems approach evaluations using particular chemicals with known efficacy rates and uncertainties. The generic approach used here is acceptable, but is less ideal than working with product-specific empirical data.

Eradication of alternate hosts for ECFF, chiefly thought to be honeysuckle (*Lonicera* spp.), may also be under consideration. The intent would be to reduce the potential for reproduction (population increase) and spatial expansion of ECFF. It’s not clear how effective this would be, nor how much effort it would require. Moreover, this might increase the pressure on available cherry hosts, or have other unintended consequences. We think the activities discussed above are presently more likely to be beneficial than this one.

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