Simulation-Based Evaluation of Two Insect Trapping Grids for Delimitation Surveys

Barney Caton (✉ barney.p.caton@usda.gov)

United States Department of Agriculture

Hui Fang

NSF Center for Integrated Pest Management, North Carolina State University

Nicholas Manoukis

Daniel K. Inouye U.S. Pacific Basin Agricultural Research Center, Agricultural Research Service, United States Department of Agriculture

Godshen Pallipparambil

NSF Center for Integrated Pest Management, North Carolina State University

Research Article

Keywords: simulation model, delimitation survey, *Acrolepiopsis assectella*, *Ceratitis capitata*, trapping grid, dispersal capability

Posted Date: March 2nd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1370099/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

In the United States, delimitation trapping surveys with square grids have been used for decades for exotic insects without rigorous evaluation. We used simulations to investigate the effectiveness of two representative designs: an 8-km grid for *Acrolepiopsis assectella* (leek moth) and a 14.5-km grid for *Ceratitis capitata* (Mediterranean fruit fly, “Medfly”). We investigated grid compositions and design factors, measuring performance as the mean probability of pest capture over all traps, $p(\text{capture})$, and designed improved grids for both species. For the basic designs, $p(\text{capture})$ was 0.86 for leek moth and 0.71 for Medfly, with the latter performing better due to greater lure and trap attractiveness. For both designs, 86 percent or more of mean $p(\text{capture})$ came from core area captures. Egress testing indicated that both grids were oversized. An improved grid for leek moths would use 80 traps in a 3.2-km diameter circle: mean $p(\text{capture})$ decreased but total cost was reduced by 91 percent. The best grid for Medfly was a 4.8-km diameter circle grid with 232 traps, which gave mean $p(\text{capture})$ of 0.66 and reduced total costs by 86 percent. Simulation may be used to improve common trapping survey plans, often saving significantly on costs while maintaining survey performance.

Introduction

When adventive populations of exotic pests are detected after introduction, delimiting surveys, to determine the boundaries of the infested area ^{1,2}, are usually an important first step in the response. The two purposes of delimiting surveys are to confirm the presence of the pest population and to determine the size of the area occupied ³. For many mobile insects this involves trapping ⁴.

In the United States, delimiting survey designs are only minimally customized based on the pest of concern or the trapping system. Typically, design choices come down to one of two standard sizes of square-shaped trapping grids. The smaller of the two has side lengths of 8.0 km (5 mi; hereafter, “8-km grid”) (Fig. 1a), and has been proposed for small moths, such as leek moth (*Acrolepiopsis assectella* (Zeller)) ⁵, plum fruit moth (*Grapholita funebrana* (Treitschke)) ⁶, summer fruit tortrix moth (*Adoxophyes orana* (Fischer von Roslerstamm)) ⁷, and *Spodoptera* spp. ⁸. The other trapping grid has side lengths of 14.5 km (9 mi; hereafter, “14.5-km grid”) (Fig. 1b), and has been specified for use with nearly every fruit fly of concern ⁹, including Mediterranean fruit fly (Medfly, *Ceratitis capitata* (Weidemann)), Oriental fruit fly (OFF, *Bactrocera dorsalis* (Hendel)), Mexican fruit fly (Mexfly, *Anastrepha ludens* (Loew, 1873)), and melon fly (*Zeugodacus cucurbitae* (Coquillett)).

The size choice between these two grids has been a broad means of accounting for pest dispersal ability, which varies widely ^{10,11}, but these grid choices may not consider several other factors that are known to affect survey performance. While trap density is important, trap attractiveness seems to be the most important single factor affecting survey performance ¹². Attractiveness is well known to vary by type of trap or lure ^{13–16}. Consequently, the density (or densities) for a particular trap type with specific attractiveness are likely chosen to achieve expected detection probabilities, while considering resource

use (costs and servicing time) ¹⁷. Other potentially important factors include trapping duration, trap grid shape, resource limitations, and/or operational constraints.

While these standard delimiting designs have been used in many cases for decades, their performance has largely been unquestioned and unstudied. While we have seen no reports of failures (insect escape), the only evidence for their effectiveness is anecdotal, in the form of continued usage without adaptations. Moreover, the creation of these designs may not have been particularly science-based. The 14.5-km grid was devised by an expert group based largely on collective experience and expectations (PPQ, personal communication). The group dealt with the uncertainty around Medfly dispersal potential by increasing the trapping grid radius three-fold to act as a reasonable safety buffer. That design also incorporates variable densities throughout, but the exact rationale for that has been lost, except perhaps as a means to limit the resources needed for a grid of that size (PPQ, personal communication). The approach to date for employing delimiting surveys could largely be described as “one-size-fits-all”.

Studying delimiting survey performance in field experiments is lengthy, difficult, and expensive. Given the number of important experimental factors and the complexity of the interactions between insects, traps, and the environment, controlled experiments on just a few important factors might take several years and would likely be limited to studying a single pest. In contrast, simulation models can be an efficient and effective means of investigating ecological phenomena, and are particularly well-suited to situations in which the interactions are complex, and when factor importance is not well understood ¹⁸. Different models have been developed and used to estimate the attractiveness of traps and probability of capture of trapping grids ^{12,13,19–23}, or to optimize the spatial deployment of traps in integrated pest management ²⁴. The simulation model, TrapGrid, was created to simulate insect trapping networks and quantify capture probabilities ¹².

Here, we used TrapGrid to evaluate the performance of two representative delimiting survey trapping designs for insects in the United States. Our objectives were to: 1) evaluate the overall performance of the default leek moth and Medfly grid designs; 2) deconstruct and manipulate the two grids to better understand how design factors affected performance; 3) investigate the appropriateness of the grid sizes in relation to insect dispersal ability; and 4) use the model to design potentially more effective and less costly designs for each species. We focused singularly on trapping for delimiting surveys and the two relevant goals: 1) confirming the presence of the pest population and 2) determining the spatial extent ³.

Materials And Methods

Trapping survey grid designs

The two designs chosen for evaluation were the 8-km grid for leek moth ⁵ and the 14.5-km grid for Medfly ⁹ (Figs. 1a & b). Those sizes are most common in published plans. The leek moth grid used a constant trap density, ρ (no. per km²), of ~ 14 traps per km² (36 per mi²), giving it 900 total traps (Fig. 1a). The

Medfly grid had variable ρ : ~ 39 traps per km^2 in the core (Band 1, but hereafter referred to as the “core”), ~ 19 in Band 2, 10 in Band 3, 8 in Band 4, and 4 in Band 5 (Fig. 1b) ⁹. The total number of traps was 1,700. Trap density affects overall survey effectiveness and directly impacts survey budgets through supply costs and required daily or weekly monitoring. Theoretically, higher ρ should increase probability of capture, $p(\text{capture})$, up to the point where trap capture zones overlap or compete with each other (“interference”). In practical terms, however, ρ is often limited by resource requirements.

Simulation model

All simulations were performed in TrapGrid, which is a landscape-level, spatially explicit model that simulates a population of insects moving in a defined trapping network ^{12,25}. The model calculates and reports the daily average escape probability for the population, $p(\text{escape})$. The mean probability of capture, $p(\text{capture})$, is $1 - p(\text{escape})$, which represents the cumulative mean daily probability of capturing any individual.

Model parameter specifications

TrapGrid has six key parameters: grid side length (l), trap density (ρ), survey duration (t), population size (N), diffusion coefficient (D), and trap attractiveness ($1/\lambda$). Outbreak locations can also be specified. Grid sizes and trap densities (ρ) were as stated above for the two species. The maximum survey duration, t , in each iteration was 120-d, but we always evaluated survey performance at 30 days, to reflect a short delimiting activity aimed at providing information for decision making. Unless otherwise specified below, simulations were run with the baseline parameters. We used TrapGrid version 2019-12-11 from GitHub (<https://github.com/manoukis/TrapGrid>). As expressed below, capture probability ($p(\text{capture})$) means the cumulative average capture probability after 30-d.

Population size

Population size, N , was equal to 50 individuals in all simulations. This reflected a first or second generation of insects early in an infestation ²⁶, as befits a delimitation exercise. Further, the version of TrapGrid we used is not sensitive to the number of individuals in the outbreak, as the average capture probability is being calculated ²⁷. That value was static in each model run, i.e., no natality or mortality ¹².

Diffusion coefficient

Insect movement is described by the diffusion coefficient, D (m^2 per day), which is the expected (maximum) daily area explored by the organism ²⁸. Reported values range from near zero into the 10,000s ¹⁰. We varied D by orders of magnitude from 5 to 50,000 m^2 per day which depends on scenarios unless otherwise specified.

Leek moth is considered to be a weak flyer²⁹. Most moths will fly no more than 100–200 m from overwintering sites³⁰. The value of D was around 500 m² per day based on the qualitative guidelines proposed by PPQ³¹.

Medfly is a moderate disperser^{32–34}, despite perhaps having a reputation as being highly motile. The D value for Medfly is 5,000 m² per day^{11,22}.

Trap attractiveness

This parameter, $1/\lambda$ (m), describes the distance at which the probability of an insect being lured and caught by a single trap is 65 percent¹². Hence, $1/\lambda$ provides a useful metric for comparing the effectiveness of different trap types, and some values have been experimentally determined^{15,35}. The standard Medfly trap uses the synthetic pheromone, trimedlure, which has $1/\lambda$ equal to 7–14 m¹². We used $1/\lambda = 10$ m for Medfly here.

Sticky wing traps baited with a pheromone lure have been recommended for leek moth⁵, but we found no information on the attractiveness of this configuration. Based on the use of a relatively strong pheromone, we qualitatively estimated that the trap had high attractiveness, with $1/\lambda = 20$ m³¹.

Outbreak locations

In every simulation, we randomized 50 population outbreak locations within the core (≈ 2.6 km² or 1 mi²). When this is done, TrapGrid runs one iteration per location²⁵. To achieve 1,000 total iterations across the 50 locations we used code to loop each simulation run 20 times, specifying a random seed for each loop (1 to 20, sequentially). Reported results are the mean of 1,000 iterations.

Simulation analyses

Comparative grid performance

We first evaluated and compared each species' baseline grid. Because Medfly is considered a more serious pest risk than leek moth, we hypothesized that $p(\text{capture})$ should be greatest for the Medfly grid. We also expected that grid size differences could be justified by the difference in dispersal abilities of the two species.

Evaluating band contributions and density impact

Secondly, we evaluated grid design factors to better understand how they affected survey performance. This first entailed creating grid maps with only single bands for each design (Fig. 2a)—each of the three bands for leek moth, each single of five bands for Medfly—with trap densities as defined above.

We also evaluated full grids with different trap densities. For the leek moth uniform densities tested were 3.5, 6.2, 9.7, 13.9, 18.9, 24.7, 31.3, and 38.6 traps per km² (these correspond to densities of 9 to 100 traps

per square mile). This test was more complicated for Medfly because of its variable density grid. First, we held all outer band densities constant, and tested only the core density, starting at 31.3 traps per km² and stopping before $p(\text{capture})$ decreased significantly from the value with the default grid. We then repeated this process in successive bands. Finally, we ran simulations with a uniform density of 38.6 traps per km² across the entire grid to gauge potential maximum performance.

Evaluating population containment

First, we wanted to know if the leek moth and Medfly grid sizes were appropriate for containing the populations. To do this we simulated each pest with a perimeter trapping grid (1.6 km wide) just larger than the default grid size (e.g., Fig. 2b) and referred to the results of band contribution. The inside perimeter for leek moth was set 4.0 km away from the epicenter, and the perimeter for Medfly was 7.24 km away from the epicenter. We used $1/\lambda = 30$ m (high trap attractiveness) to ensure egressing insects were highly likely to be captured in simulations. Default D values were used for the two species. The leek moth grid had $\rho = 13.9$ in the perimeter, while $\rho = 38.6$ was used for the Medfly grid.

Second, we wanted to determine sufficient containment sizes generally across varying dispersal abilities. To do this, we found the smallest D at which the $p(\text{capture})$ was non-zero (≥ 0.001) for each of the individual band grids created above. The value 0.001 was arbitrary but sensitive enough for our purposes here. Default trap attractiveness values were used in the grid for each species.

Simulation-based improved grid designs

To potentially improve each of the designs, we assessed cost effectiveness of different modifications using information about trap supply and servicing prices. The unit cost for buying and servicing the leek moth traps (sticky wings baited with pheromone) for one month was around \$28 (Ontario Ministry of Agriculture, Food & Rural Affairs, personal communication). The same cost for a Medfly trap (ChamP™ or Jackson traps, baited with synthetic pheromone, trimedlure) was \$26 (California Department of Food and Agriculture, personal communication). We evaluated the return on investment (ROI) as capture percentage obtained per \$1,000 spent. We focused on testing ROI that the grid was large enough and did not consider egress for simplicity.

The modifications evaluated were changes in trap densities, grid sizes, and grid shapes. We previously found that circular grids are more efficient than square ones³⁶. For the leek moth grid, we simulated $\rho = 6.2, 9.7, 13.9, 18.9, 24.7, 31.3$, and 38.6 traps per km² in 3.2 km diameter and 8.0 km diameter circular grids. For Medfly, we replaced the square grid with circular grids consisting of circular bands, simulated 4.8 km diameter grids with the default densities for each included band, and reduced densities to $\rho = 13.9$ or 9.7 in Band 2 while keeping other settings the same. We also assessed a circular grid in which the core density was 38.6, while the density in a 1.5 mi-wide band outside the core was 6.2.

Results

Comparative grid performance

In their baseline settings, $p(\text{capture})$ was 0.86 for the leek moth grid, versus 0.71 for the Medfly grid. Medfly grid performance was lower than that of the leek moth grid despite that Medfly had greater D , a larger grid, and higher trap density in the core. Notably, though, trap attractiveness was greater for leek moth. Lower trap attractiveness for Medfly probably helps explain the greater densities used in the design, to improve the capture rate for the high-risk pest.

Captures by band and impact of density on performance

Band contributions

Overall $p(\text{capture})$ values for full grids were less than the sum for all bands (e.g., 0.71 vs. 0.78 for Medfly) because captures occurred in multiple bands when simulating the full grid (Table 1).

The core of the Medfly grid always contributed the most to overall $p(\text{capture})$, with a value of 0.67 (94 percent of the total $p(\text{capture})$ in the whole grid) on its own (Table 1). When solitary, Band 2 had $p(\text{capture}) = 0.09$, and all three of the other bands had $p(\text{capture}) = 0.0$ (Table 1).

In the leek moth grid, the core had $p(\text{capture}) = 0.85$, which was nearly 99 percent of $p(\text{capture})$ for the whole grid (above). When solitary, Band 2 had $p(\text{capture}) = 0.03$, and Band 3 had $p(\text{capture}) = 0.0$.

Table 1
The probability of capture for the standard Medfly grid, for different bands, and for the grid with a uniform density of 38.6 trap per km²

Description	Band	Traps (no.)	Trapped area (km ²)	$p(\text{capture})$
Standard full grid	N/A	1,660	209.8	$0.71 \pm 0.002^*$
Individual bands	Core	100	2.6	0.67 ± 0.003
	2	392	20.7	0.09 ± 0.003
	3	400	41.4	0.00 ± 0.000
	4	480	62.2	0.00 ± 0.000
	5	288	82.9	0.00 ± 0.000
Uniform density grid	N/A	8,100	209.8	0.74 ± 0.002
*mean $\pm$ 95 percent confidence limits				

Density effects

All else being equal, $p(\text{capture})$ increased with greater trap density (ρ), but the marginal increases were smaller at higher densities (Figs. 3 & 4). For leek moth, $p(\text{capture})$ was only 0.36 at 3.5 traps per km^2 , and it plateaued at around 0.97 with $\rho = 24.7$ traps per km^2 (Fig. 3).

For Medfly, reducing the core density decreased $p(\text{capture})$ markedly with each level of reduction, to a low value of 0.26 at 6.2 traps per km^2 (Fig. 4a). Conversely, reducing the density of Band 2 caused only very small decreases in overall $p(\text{capture})$ (Fig. 4b). The total decline in overall $p(\text{capture})$ from 18.9 to zero traps per km^2 in Band 2 was only 0.04 ($= 0.71 - 0.67$). Reducing densities in Bands 3 to 5 had negligible effects on overall $p(\text{capture})$ (not shown). Finally, using the core density throughout the entire grid only increased $p(\text{capture})$ by 0.03 compared to the standard design (Table 1).

Population containment

Size appropriateness of the leek moth grid

The perimeter test indicated that over the 30-d survey duration the likelihood of leek moth egressing from the 8-km grid was zero. This confirmed the results from the band contribution tests above. On that basis, simulation results suggest that the 8-km grid is oversized, and a 3.2-km grid is adequate. If resources are available and field a manager wants to be more conservative, a 4.8-km grid is more than enough.

The dispersal ability assessment also demonstrated that the current leek moth grid was oversized. The probability of capture in Band 1 dropped from 0.85 at $D = 500$, to 0.80 at $D = 5,000$, and to 0.44 at $D = 50,000$. This reflected that insects with moderate to high dispersal abilities were likely to move beyond the core. In contrast, $p(\text{capture})$ in Band 3 only became non-zero for pests with $D \geq 8,200$, meaning that it was unnecessary for leek moth, with $D = 500$. Lastly, Band 2 had non-zero $p(\text{capture})$ for insect pests with $D \geq 25$. The $p(\text{capture})$ value for Band 2 peaked at 0.68 for $D = 50,000$ but was only 0.03 for $D = 500$.

Size appropriateness of the Medfly grid

The perimeter test confirmed that the likelihood of egress from the standard grid over 30 days was zero for Medfly.

The band contribution results showed that for insects with $D \leq 50,000$, $p(\text{capture})$ values in Bands 3, 4, and 5 were zero (Table 1). This suggested that this grid was oversized for Medflies and other insects with $D \leq 50,000$. Since Bands 3 through 5 did not contribute any $p(\text{capture})$ at all (Table 1), they could be eliminated for Medfly and insects with similar dispersal abilities, resulting in a 4.8-km grid.

General size requirements as a function of D

For grids with leek moth traps ($1/\lambda = 20$ m), $p(\text{capture})$ in Band 2 became non-zero for $D = 25$ m^2 per day. For Band 3, the value was $D = 8,200$ m^2 per day (to the nearest hundred).

For Medfly traps ($1/\lambda = 10$ m), $p(\text{capture})$ in Band 2 became non-zero with $D = 87$ m² per day. For the other bands, non-negligible $p(\text{capture})$ occurred with D values of 11,950 in Band 3, 38,400 in Band 4, and 96,400 in Band 5. Thus, those bands were only required for insects with very high dispersal abilities.

Optimal grid designs

Leek moth

The standard grid with 900 traps had a total cost of \$25,200. Given $p(\text{capture})$ of 0.85, this design achieved 3.4 percentage points per \$1,000 spent ($= 85/25.2$).

We optimized the design by manipulating the grid size and trap density in circular grids. Based on the egress likelihood and grid size tests above, we adopted a 3.2-km diameter for leek moth, because that was adequate for containment in simulations. The 3.2-km grid and the circular 8.0-km diameter grid had equivalent $p(\text{capture})$ values (Table 2).

As expected, trap density strongly affected $p(\text{capture})$, which increased from 0.56 at 6.2 traps per km², to 0.85 with 13.9 traps per km² (default). It reached 1.0 with 38.6 traps per km² for both grid sizes. However, ROI declined as density increased (Table 2), which suggested that an intermediate density was preferable. We judged that the best-performing density was 9.7 traps per km² (Fig. 5a), which achieved $p(\text{capture}) = 0.73$ with only 80 traps, giving it an ROI of 32.6 percentage points per \$1,000 spent ($= 73/2.24$). The total survey cost of \$2,240 was 91 percent smaller than that for the standard design (Table 2). At that density, increasing the grid size to 8 km would not give any marginal benefit since the $p(\text{capture})$ was the same.

The best performing grid based solely on ROI was a 3.2-km diameter circular grid with 6.2 traps per km², with ROI equal to 38.3 percentage points per \$1,000 spent. This design used only 52 traps, cost \$1,456, and still gave $p(\text{capture}) = 0.56$ (Table 2). Although $p(\text{capture})$ was relatively low, the design is still “more likely than not” to detect the population. Thus, this design might be particularly useful when survey budgets are very small.

Table 2
Comparison of circular grids with diameters of either 3.2 km or 8.0 km for leek moth

Trap density (no./km ²)	3.2 km diameter				8.0 km diameter			
	Traps (no.)	Cost (\$)	p(capture)	ROI*	Traps (no.)	Cost (\$)	p(capture)	ROI
6.2	52	1,456	0.56	38.3	316	8,848	0.56	6.3
9.7	80	2,240	0.73	32.7	489	13,692	0.73	5.3
13.9	112	3,136	0.85	27.3	716	20,048	0.85	4.3
18.9	156	4,368	0.93	21.3	967	27,076	0.94	3.5
24.7	208	5,824	0.97	16.7	1,268	35,504	0.97	2.7
31.3	256	7,168	0.99	13.8	1,589	44,492	0.99	2.2
38.6	316	8,848	1.00	11.3	1,972	55,216	1.00	1.8
*ROI: return on investment, capture percentage for each \$1000 spent								

Medfly

The standard Medfly grid with 1,700 traps (variable densities) would cost \$44,200 for a 30-d survey. This gave ROI of only 1.6 percentage points per \$1,000 spent (= 71/44.2) (Table 3).

To optimize the Medfly design, we first reduced the grid size to 4.8-km (Bands 4 and 5 removed). Using the default trap density in the core and 9.7 traps per km² in bands 2 and 3 gave $p(\text{capture}) = 0.66$, which was very similar to $p(\text{capture})$ for the standard grid (Fig. 5b; Table 3). This design used 232 traps and would only cost \$6,032, a savings of \$38,168 (86 percent). It gave ROI of 10.9 percentage points per \$1,000 (= 66/6.032), which was the most efficient design of those considered. This option for Medfly is “Alternative 1” (Table 3).

Other alternatives all had substantially lower performance in terms of ROI. Given the high-risk pest status of Medfly, some managers might choose a larger 6.4-km grid. That size grid also achieved $p(\text{capture}) = 0.65$ with 100 traps per km² in the core, and 6.2 traps per km² in bands 2–4. This design (“Alternative 2”) used 272 total traps and would cost \$7,072, a savings of \$37,128 (84 percent reduction). Compared to the default Medfly grid, the ROI for this design was 9.2 percentage points per \$1,000 spent (= 65/7.072), which was still six times greater than that for the standard Medfly grid (Table 3).

Table 3
Alternative delimiting survey design options for Medfly

Design	Grid size	Outer bands density	Total traps	$p(\text{capture})$	Cost		ROI [‡]
	(km)	(no./km ²)*	(no.)		Total (\$)	Reduction [†]	
Standard	14.5	Variable	1,700	0.71	44,200	—	1.6
Alternative 1	4.8	9.7	232	0.66	6,032	0.86	10.9
Alternative 2	6.4	6.2	272	0.65	7,072	0.84	9.2
* All alternatives had same density of 38.9 traps per km ² in the core							
† Reduction relative to default survey cost							
‡ ROI: return on investment, capture percentage points for each \$1,000 spent							

Discussion

The performance of the current Medfly design was unexpectedly inferior to that of the leek moth even with a more vagile target insect, 2.8 times greater trap density in the core, and a grid size over three times larger. The leek moth grid performed better despite all those factors because of much greater trap attractiveness. Thus, trap attractiveness was the key determinant for delimiting survey performance, as it was for detection ¹².

The Medfly grid designers likely understood that the available trap was not highly attractive, and chose higher densities to try to reach their desired (non-quantitative) survey performance level. By contrast, the designers of the leek moth grid used a (constant) density three times smaller, likely because the trap was known to be much more attractive. Higher densities can help compensate for less attractive traps, but the impact is limited when attractiveness is low ³⁶.

The cores of both the leek moth grid and the Medfly grid accounted for more than 86 percent of overall $p(\text{capture})$, and even the second band had greater $p(\text{capture})$ than outer bands. Therefore, in many delimiting activities we can expect that most captures will occur in the core and Band 2. This should not be surprising. Small insect populations are unlikely to move very far ^{26,37}, especially if hosts are available ^{34,38,39}. In addition, the short duration of a delimitation survey limits dispersal potential for the insects (see below). Core area captures confirm the presence of the target pest population but may not contribute much to boundary setting.

No captures occurred in Band 3 of the leek moth grid and Bands 3 to 5 of the Medfly grid, which indicated that those bands could be eliminated. The resulting smaller grids would be more cost-effective without

compromising performance. Smaller survey grid radii can be predicted based on insect dispersal abilities⁴⁰.

All else being equal, increasing the trap density will generally improve $p(\text{capture})$ for any survey grid. However, large surveys can become prohibitively expensive for agencies to run⁴¹. In that context, the use of variable densities in the Medfly grid is understandable. At its standard size, the survey grid would require 8,100 traps if the core trap density were constant (Table 1). The designers likely intuited that captures in outer band were less likely, and that lower densities could be used in those bands. However, that reduces the likelihood of detection in outer bands, and could increase the possibility of undetected egress, especially with longer survey durations. As far as we know, natural egress has not been raised as a concern following the numerous Medfly quarantines that have used this survey grid over the years, in Southern California in particular⁴².

There are limited situations in which increasing densities to improve $p(\text{capture})$ would be worthwhile. Generally, $p(\text{capture})$ increases with density because the insects have more chances to interact with traps. However, gains are limited for less attractive traps, and the marginal ROI decreased quickly as densities increased (Table 2). Higher densities in the core had much more impact on grid performance, but once the presence of the population has been confirmed additional captures are unnecessary. Therefore, low or intermediate density may be optimal for the core. For the outer bands, increasing densities would improve detection of potential escapees but larger grid sizes already limit cost efficiency (Table 2). Further increasing those densities would reduce cost efficiencies even more. Investigating the relationship between the outer band densities and the accuracy of boundary setting could help resolve how to balance costs.

One way to improve $p(\text{capture})$ and the accuracy of boundary setting, while also cutting costs, would be to develop more attractive traps. Poorly attractive traps include food-based attractants⁴³, and traps based solely on visual stimuli³¹. But developing better traps is difficult to achieve. Pheromone-based attractants generally perform best⁴⁴, but these are unavailable for many insects. For instance, scientists have searched for decades for effective pheromones for *Anastrepha suspensa* (Loew) and *A. ludens* (Loew) without success⁴⁵. Common issues include the complexity of components, costs of synthesis, and chemical stability.

The 14.5-km grid with variations has been widely used for many other insects in the CDFA (2013) guidelines, such as Mexican fruit fly (*Anastrepha ludens*), Oriental fruit fly (*Bactrocera dorsalis*), and melon fly (*Zeugodacus cucurbitae*). In the current study, a 4.8-km grid provided adequate containment of pest populations with moderate or lower dispersal abilities, including Medfly. Leek moth, with even lower dispersal ability, might require only a 3.2-km grid. Grids larger than 4.8-km only seemed necessary for highly vagile insects, those with $D \geq 50,000 \text{ m}^2$ per day³⁶. Dominiak and Fanson⁴⁶ analyzed trapping data for Queensland fruit fly (Qfly, *Bactrocera tryoni* (Froggatt)) and obtained a similar result: the recommended quarantine area distance of 15 km was oversized, and could be reduced to 3 to 4 km. In

that case, managers had also seemed to overestimate the needed size based on uncertainty about likely pest dispersal distances.

One likely reason for the large size of the standard Medfly grid is that it is also used for monitoring and management ⁴⁷. Medfly quarantines end after at least three generations without a detection, so the surveys may last for 90 days or more. The standard grid size was reportedly originally determined by multiplying the estimated dispersal distance by three (PPQ, personal communication), to account for uncertainty. This implies that the estimated distance was about 2,400 m (duration unknown).

Examining diffusion-based movement for these two insects in TrapGrid can give insight into why simulations indicated that smaller grids may be adequate ³⁶, which has been verified empirically ⁴⁰. The expected spread of insect pests is a normal distribution centered from the epicenter ⁴⁸ with a standard deviation (σ) proportional to the time (t) elapsed, as follows ¹²:

$$\sigma = 4 \times (Dt)^{0.5} [1]$$

The value of σ for Medfly after 30 days is only about 1,550 m. In a normal distribution, $\sigma = 1,550$ m gives a 95th percentile distance of 2,550 m, which is similar to the estimated distance above of 2,400 m. Over 90 days, $\sigma = 2,700$ m for Medfly, which gives a 95th percentile distance of 4,441 m, still much shorter than the grid radius of 7,250 m. A 95th percentile of 7,250 m requires $\sigma \approx 4,408$ m, which equals $t = 253$ days. In addition, the maximum total distance we observed in trapping detections data for Medfly in Florida was about 4,800 m ⁴⁰. Hence, depending on survey objectives, some Medfly grid sizes could be significantly reduced, while achieving significant cost savings and maintaining containment. While a large grid size has been suggested for most exotic fruit flies ⁹, the most vagile species may be the Oriental fruit fly, which requires a delimiting survey radius of only 4 km ⁴⁰.

The same calculations for leek moth give $\sigma \approx 490$ m for 30 days, with a 95th percentile distance of only 806 m. That is half the distance of the recommended shortened radius above of 1.6 km (i.e., a 3.2-km grid), and nearly five times less than the radius of the standard 8-km grid. A 95th percentile of 4,000 m requires $\sigma = 2,432$ m, which implies $t = 740$ days, which is about two years. Therefore, the leek moth grid is arguably even more oversized than the Medfly grid.

Although it seemed too large for leek moth, an 8-km grid for delimitation could be appropriate for some other moths. For example, the delimiting survey plans for *Spodoptera littoralis* and *S. exempta* use this size ⁸. *S. littoralis* is described as dispersing “many miles” and *S. exempta* can travel hundreds of miles ⁸, which clearly exceeds the described dispersal ability of leek moth. On the other hand, the survey plan for summer fruit tortrix moth (*Adoxophyes orana*) also specifies an 8-km grid for delimitation, but contains little information on dispersal, suggesting only that most movement is local ⁷. Like leek moth, a 3.2-km grid for that species seems likely to be more appropriate.

Many survey designs in use were often primarily based on local experience⁴⁹ rather than “hard” science. Scientists have recognized the need for more cost-effective surveillance strategies^{50,51}. Results here demonstrated that the sizes and densities of these two survey grids could be optimized to save up to \$22,960 per survey for the leek moth, and \$38,168 per survey for the Medfly. In practical terms, that means more than 11 leek moth surveys could be run for the cost of one under the previous plan, while over seven Medfly surveys could be funded by the budget of one the original plan. The magnitudes of reduction seen here may be typical, since about 90 percent of the costs in trapping surveys are for transportation and maintenance related to traps⁵².

Circular grids perform as well as square grids but use fewer traps and less service area to achieve equivalent $p(\text{capture})$ ³⁶. Moreover, detections in the corners of a square grid are evidence that insects could have traveled beyond the square along the axes, resulting in uncertain boundary setting. Most published survey grids are square^{9,53} but many field managers tend to use approximately circular trapping grids in the field (PPQ, personal communication). Converting to a circular grid with a radius of half the side length reduces the area and number of traps by around 21 percent³⁶. Our findings here were consistent with that. The circular leek moth grid used 80 traps while the square grid would require 100 traps at the same density (9.7 trap per mi²). For Medfly, only 232 traps were needed for 4.8 km circular grid (Table 3), while a square grid would require 300 (not shown).

Grid size reductions have little impact on $p(\text{capture})$, since outer band detections contributed little to overall performance. Egress potential is the main consideration when setting survey size, and the simulation results indicated that the standard survey sizes for these two pests were excessive. The optimal designs for these two species both used smaller grids. We have verified these results empirically using trapping detections data for six species with varying dispersal abilities⁴⁰, and, as mentioned above, similar results were observed for Qfly quarantine area size⁴⁶. Many delimiting survey plans may be oversized because they were developed before much dispersal research had been done³². Because size reductions eliminate traps in proportionally larger outer areas, the impact on survey costs is substantial. In the case of leek moth, removing the outermost band, with 400 traps, would directly reduce the cost by \$11,200.

Quantitatively assessing $p(\text{capture})$ in different designs for the same target pest allows us to find trap densities that lower costs while maintaining performance. This quantification was not possible until very recently, so survey performance has only been discussed very generally in the literature^{4,54} and no standard thresholds exist. We think a reasonable minimum threshold for the choice of $p(\text{capture})$ might be $p(\text{capture}) > 0.5$, to try to ensure that population detection is “more likely than not”. It seems designs that try for $p(\text{capture}) = 1.0$ could be realistic for traps with high attractiveness but seem very likely to have lower ROIs (e.g., Table 2). Even for the most serious insect pests, we think targeting near-perfect population detection during delimitation is likely not justified. Rather than specifying a single, optimal performance level, designs achieving $p(\text{capture})$ from 0.6 to 0.75 could be effective in terms of both cost and performance (see above).

However, some delimiting survey designs in the United States may not be performing as well as expected³⁶. For instance, the delimiting survey design for Mexican fruit fly (*Anastrepha ludens* (Loew, 1873)) uses approximately 31 traps per km² in the core of a 14.5 km square grid⁹ but the traps are poorly attractive ($1/\lambda = 5$ m). In this scenario, with a 30-d survey duration, $p(\text{capture})$ is only around 0.23³⁶. A much greater density (> 80 traps per km²) could be used to achieve $p(\text{capture}) \geq 0.5$, but this may not be feasible, depending on the survey budget.

The current version (Ver. 2019-12-11) of TrapGrid is not sensitive to population size and does not consider effect of ambient factors. The recommendations for leek moth and Medfly are based on the relatively small population size and in situations where a consistent early detection is spotted. If the outbreak population is very large and have extensively spread out, area-wide delimitation survey should be considered, which we are currently studying. Additionally, except for the model parameters specified above, many factors can impact trapping survey, such as weather conditions, topography of the environment, availability of host plants, seasonality of pest, and population dynamics. These factors are not considered in the current version of TrapGrid.

Still, our results indicated that inner area detections are likely to predominantly determine $p(\text{capture})$. Delimiting surveys may often yield few detections, because adventive populations can be very small and subject to high mortality²⁶. Captures assure managers that the surveys are viable, but while inner area detections confirm the presence of the population, they seem much less useful for defining spatial extent. Usually the furthest detections from the presumed source are used to delimit the incursion^{53,55}. Thus, increasing inner area densities to inflate $p(\text{capture})$ may not produce a more effective survey, even if ROI seems comparable (Table 2). The most effective surveys will achieve the two goals of delimitation and limit the likelihood of egress while minimizing both trap density and grid size.

Using TrapGrid simulations to decouple and isolate different survey design factors in the two grids examined here demonstrated the utility of simulations to investigate something that would be extraordinarily costly and time-consuming to experiment with in the field. It may not be possible to use TrapGrid to optimize delimiting survey designs for all combinations of dispersal abilities and trap attractiveness levels, because of the very large number of simulations that would require, but our results demonstrate that such optimization is possible for select insects. Although TrapGrid has not been completely validated for all insects and situations, it has performed well with two studied species¹², and its accuracy with regard to recommending smaller grid sizes has now also been empirically verified⁴⁰. Follow-up field studies could always be done to try to validate more surprising results.

Declarations

Acknowledgements

The authors thank David Bartels, Sunil Kumar, and Melissa Warden for their reviews, which made the work better. Opinions, findings, conclusions, or recommendations expressed in this publication are those

of the authors and do not necessarily reflect the views of the USDA. USDA is an equal opportunity employer.

Author's Contributions

All authors conceived and designed research; HF and BC analyzed the data. All authors contributed critically to the drafts and gave final approval for publication.

Data availability statement

The model results generated and analyzed during the current study are available from the corresponding author on reasonable request.

Funding

Funding was received for part of this work from the following USDA PPA 7721 grant: AP20PPQS&T00C111.

Competing interests

The authors have declared that no competing interests exist.

References

1. IPPC. International Standards for Phytosanitary Measures, Publication No. 6 Surveillance. Report No. Publication No. 12, 14 (Food and Agriculture Organization (FAO) of the United Nations, Secretariat of the International Plant Protection Convention (IPPC), Rome, Italy, 2018).
2. IAEA. Trapping guidelines for area-wide fruit fly programmes. 47 (Insect Pest Control Section, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency (IAEA), Vienna, Austria, 2003).
3. van Havre, Z. & Whittle, P. in *Biosecurity Surveillance: Quantitative Approaches* (eds F. Jarrad, S. Low-Choy, & K. Mengersen) 123-133 (CABI, 2015).
4. Shelly, T., Epsky, N., Jang, E. B., Reyes-Flores, J. & Vargas, R. *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures, Area-Wide Programs, and Trade Implications*. 3-627 (Springer, 2014).
5. PPQ. New Pest Response Guidelines: Leek Moth *Acrolepiopsis assectella* (Zeller). 83 (Plant Protection and Quarantine (PPQ), Animal and Plant Health Inspection Service, U.S. Department of Agriculture, Riverdale, MD, 2004).

6. PPQ. New Pest Response Guidelines: Plum Fruit Moth (*Cydia funebrana*). 125 (Plant Protection and Quarantine (PPQ), Animal and Plant Health Inspection Service, U.S. Department of Agriculture, Riverdale, MD, 2012).
7. PPQ. New Pest Response Guidelines: Summer Fruit Tortrix Moth (*Adoxophyes orana*). 142 (Plant Protection and Quarantine (PPQ), Animal and Plant Health Inspection Service, U.S. Department of Agriculture, Riverdale, MD, 2012).
8. PPQ. New Pest Response Guidelines: Spodoptera. 82 (Plant Protection and Quarantine (PPQ), Animal and Plant Health Inspection Service, U.S. Department of Agriculture, Riverdale, MD, 2005).
9. CDFA. *Insect Trapping Guide (Thirteenth Edition)*. (Pest Detection/Emergency Projects Branch, California Department of Food and Agriculture (CDFA), State of California, 2013).
10. Kareiva, P. M. Local movement in herbivorous insects: applying a passive diffusion model to mark-recapture field experiments. *Oecologia* **57**, 322-327, doi:<https://doi.org/10.1007/BF00377175> (1983).
11. Corbett, A. & Plant, R. E. Role of movement in the response of natural enemies to agroecosystem diversification: a theoretical evaluation. *Environ. Entomol.* **22**, 519-531, doi:<https://doi.org/10.1093/ee/22.3.519> (1993).
12. Manoukis, N. C., Hall, B. & Geib, S. M. A computer model of insect traps in a landscape. *Sci. Rep.* **4**, 7015, doi:<https://doi.org/10.1038/srep07015> (2014).
13. Schlyter, F. Sampling range, attraction range, and effective attraction radius: Estimates of trap efficiency and communication distance in coleopteran pheromone and host attractant systems. *J. Appl. Entomol.* **114**, 439-454, doi: <https://doi.org/10.1111/j.1439-0418.1992.tb01150.x> (1992).
14. Shelly, T. E. & Edu, J. Mark-release-recapture of males of *Bactrocera cucurbitae* and *B. dorsalis* (Diptera: Tephritidae) in two residential areas of Honolulu. *J. Asia-Pacif. Entomol.* **13**, 131-137, doi:<https://doi.org/10.1016/j.aspen.2009.12.003> (2010).
15. Manoukis, N. C., Siderhurst, M. & Jang, E. B. Field estimates of attraction of *Ceratitis capitata* to trimedlure and *Bactrocera dorsalis* (Diptera: Tephritidae) to methyl eugenol in varying environments. *Environ. Entomol.* **44**, 695-703, doi:<https://doi.org/10.1093/ee/nvv020> (2015).
16. Shelly, T. E. & Edu, J. Capture of mass-reared vs. wild-like males of *Ceratitis capitata* (Dipt., Tephritidae) in trimedlure-baited traps. *J. Appl. Entomol.* **133**, 640-646, doi:<https://doi.org/10.1111/j.1439-0418.2009.01414.x> (2009).
17. Berec, L., Kean, J. M., Epanchin-Niell, R., Liebhold, A. M. & Haight, R. G. Designing efficient surveys: spatial arrangement of sample points for detection of invasive species. *Biol. Invasions* **17**, 445-459, doi:<https://doi.org/10.1007/s10530-014-0742-x> (2015).
18. Seidl, R. To model or not to model, that is no longer the question for ecologists. *Ecosystems* **20**, 222-228, doi:<https://doi.org/10.1007/s10021-016-0068-x> (2017).
19. Branco, M., Jactel, H., Franco, J. C. & Mendel, Z. Modelling response of insect trap captures to pheromone dose. *Ecol. Model.* **197**, 247-257, doi:<https://doi.org/10.1016/j.ecolmodel.2006.03.004> (2006).

20. Cunningham, R. T. & Couey, H. M. Mediterranean fruit fly (Diptera: Tephritidae): distance/response curves to Trimedlure to measure trapping efficiency. *Environ. Entomol.* **15**, 71-74, doi:<https://doi.org/10.1093/ee/15.1.71> (1986).
21. Meats, A. & Edgerton, J. E. Short- and long-range dispersal of the Queensland fruit fly, *Bactrocera tryoni* and its relevance to invasive potential, sterile insect technique and surveillance trapping. *Aust. J. Exp. Agric.* **48**, 1237-1245, doi:<https://doi.org/10.1071/EA07291> (2008).
22. Plant, R. E. & Cunningham, R. T. Analyses of the dispersal of sterile Mediterranean fruit flies (Diptera: Tephritidae) released from a point source. *Environ. Entomol.* **20**, 1493-1503, doi:<https://doi.org/10.1093/ee/20.6.1493> (1991).
23. Wall, C. & Perry, J. N. Range of action of moth sex-attractant sources. *Entomol. Exp. Appl.* **44**, 5-14, doi:<https://doi.org/10.1111/j.1570-7458.1987.tb02232.x> (1987).
24. Guimapi, R. A. *et al.* Optimizing spatial positioning of traps in the context of integrated pest management. *Ecol. Complex.* **41**, 100808, doi:<https://doi.org/10.1016/j.ecocom.2019.100808> (2020).
25. Hall, B. D. & Manoukis, N. *TrapGrid: Simulates layout of traps in an area with insect outbreak and dispersal; calculates capture probability*, <<http://bruab.github.io/TrapGrid/>> (2019).
26. Meats, A. W., Clift, A. D. & Robson, M. K. Incipient founder populations of Mediterranean and Queensland fruit flies in Australia: the relation of trap catch to infestation radius and models for quarantine radius. *Aust. J. Exp. Agric.* **43**, 397-406, doi:<https://doi.org/10.1071/EA02070> (2003).
27. Manoukis, N. C. & Hill, M. P. Probability of Insect Capture in a Trap Network: Low Prevalence and Detection Trapping with TrapGrid. *arXiv:2110.11432 [q-bio.QM]* (2021).
28. Holmes, E. E. Are diffusion models too simple? A comparison with telegraph models of invasion. *Am. Nat.* **142**, 779-795, doi:<https://doi.org/10.1086/285572> (1993).
29. CABI. *Crop Protection Compendium Datasheet—Acrolepiopsis assectella (leek moth)*, <<https://www.cabi.org/isc/datasheet/3017>> (2020).
30. Allen, J., Fraser, H. & Appleby, M. *OMAFRA factsheet 08-009, Leek moth—A pest of Allium crops*, <<http://www.omafra.gov.on.ca/english/crops/facts/08-009.htm>> (2008).
31. PPQ. Creating delimiting trapping surveys for insects and other mobile plant pests using the perimeter-and-core design. 31 (Plant Protection and Quarantine (PPQ), Animal and Plant Health Inspection Service, U.S. Department of Agriculture; Agricultural Research Service (ARS), U.S. Department of Agriculture; Center for Integrated Pest Management (CIPM), North Carolina State University, Raleigh, NC, 2020).
32. Meats, A. in *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures: Area-wide Programs, and Trade Implications* (eds Todd Shelly *et al.*) Ch. 8, 253-275 (Springer Netherlands, 2014).
33. Baker, P. S., Chan, A. S. T. & Jimeno Zavala, M. A. Dispersal and orientation of sterile *Ceratitidis capitata* and *anastrepha ludens* (Tephritidae) in Chiapas, Mexico. *J. Appl. Ecol.* **23**, 27-38, doi:<https://doi.org/10.2307/2403078> (1986).

34. Weldon, C. W., Schutze, M. K. & Karsten, M. in *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures, Area-wide Programs, and Trade Implications* (eds T Shelly *et al.*) Ch. 6, 175-217 (Springer, 2014).
35. Manoukis, N. C. & Gayle, S. M. Attraction of wild-like and colony-reared *Bactrocera cucurbitae* (Diptera: Tephritidae) to cue lure in the field. *J. Appl. Entomol.* **140**, 241-249, doi:<https://doi.org/10.1111/jen.12251> (2016).
36. Caton, B. P., Fang, H., Manoukis, N. C. & Pallipparambil, G. R. Simulation-based investigation of the performance of delimiting trapping surveys for insect pests. *J. Econ. Entomol.* **114**, 2581-2590, doi:<https://doi.org/10.1093/jee/toab184> (2021).
37. Meats, A. Cartesian methods of locating spot infestations of the papaya fruit fly *Bactrocera papayae* Drew and Hancock within the trapping grid at Mareeba, Queensland, Australia. *Gen. Appl. Ent.* **28**, 57-60, doi:<https://doi.org/10.3316/INFORMIT.215997533240785> (1998).
38. Dominiak, B. C. Review of dispersal, survival, and establishment of *Bactrocera tryoni* (Diptera: Tephritidae) for quarantine purposes. *Ann. Entomol. Soc. Am.* **105**, 434-446, doi:<https://doi.org/10.1603/AN11153> (2012).
39. Mazzi, D. & Dorn, S. Movement of insect pests in agricultural landscapes. *Ann. Appl. Biol.* **160**, 97-113, doi: <https://doi.org/10.1111/j.1744-7348.2012.00533.x> (2012).
40. Caton, B. P., Fang, H., Manoukis, N. C. & Pallipparambil, G. R. Quantifying insect dispersal distances from trapping detections data to predict delimiting survey radii. *J. Appl. Entomol.*, 1-14, doi:<https://doi.org/10.1111/jen.12940> (2021).
41. Lance, D. R. in *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures, Area-wide Programs, and Trade Implications* (eds Todd Shelly *et al.*) Ch. 16, 559-588 (Springer, 2014).
42. Carey, J. R., Papadopoulos, N. & Plant, R. The 30-year debate on a multi-billion-dollar threat: Tephritid fruit fly establishment in California. *Am. Entomol.* **63**, 100-113, doi:<https://doi.org/10.1093/ae/tmx036> (2017).
43. Epsky, N. D., Morrill, W. L. & Mankin, R. W. in *Encyclopedia of Entomology* (ed John L. Capinera) 3887-3901 (Springer, 2008).
44. Hanks, L. M. & Millar, J. G. Sex and aggregation-sex pheromones of cerambycid beetles: basic science and practical applications. *J. Chem. Ecol.* **42**, 631-654, doi:<https://doi.org/10.1007/s10886-016-0733-8> (2016).
45. Tan, K. H., Nishida, R., Jang, E. B. & Shelly, T. E. in *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures, Area-wide Programs, and Trade Implications* (eds Todd Shelly *et al.*) Ch. 2, 15-74 (Springer, 2014).
46. Dominiak, B. C. & Fanson, B. G. Current quarantine and suspension distances are excessive for incipient populations of Queensland fruit fly (*Bactrocera tryoni* (Froggatt)) (Diptera: Tephritidae) in southern New South Wales, Australia. *Crop Prot.* **138**, 105341, doi:<https://doi.org/10.1016/j.cropro.2020.105341> (2020).

47. PPQ. Mediterranean fruit fly action plan. 83 (Animal and Plant Health Inspection Service (APHIS), Plant Protection and Quarantine (PPQ), U.S. Department of Agriculture, 2003).

48. Rudd, W. G. & Gandour, R. W. Diffusion model for insect dispersal. *J. Econ. Entomol.* **78**, 295-301, doi:<https://doi.org/10.1093/jee/78.2.295> (1985).

49. Jang, E. B., Enkerlin, W., Miller, C. & Reyes-Flores, J. in *Trapping and the Detection, Control, and Regulation of Tephritid Fruit Flies: Lures, Area-wide Programs, and Trade Implications* (eds Todd Shelly *et al.*) Ch. 17, 589-608 (Springer, 2014).

50. Poland, T. M. & Rassati, D. Improved biosecurity surveillance of non-native forest insects: a review of current methods. *J. Pest Sci.* **92**, 37-49, doi:<https://doi.org/10.1007/s10340-018-1004-y> (2019).

51. Quilici, S. & Donner, P. Analysis of exotic fruit fly trapping networks. *EPPO Bulletin* **42**, 102-108, doi:<https://doi.org/10.1111/j.1365-2338.2012.02532.x> (2012).

52. Mayo, J. H., Straka, T. J. & Leonard, D. S. The cost of slowing the spread of the gypsy moth (Lepidoptera: Lymantriidae). *J. Econ. Entomol.* **96**, 1448-1454, doi:<https://doi.org/10.1603/0022-0493-96.5.1448> (2003).

53. EFSA *et al.* General guidelines for statistically sound and risk-based surveys of plant pests. 65 (European Food Safety Authority (EFSA), Parma, Italy, 2020).

54. Kean, J. M. *et al.* in *Biosecurity Surveillance: Quantitative Approaches* (eds F Jarrad, S Low-Choy, & K Mengersen) 238-252 (CABI, 2015).

55. Lázaro, E. *et al.* General Guidelines for Statistically Sound and Risk-based Surveys of Plant Pests. Report No. 2397-8325, 65 (European Food Safety Authority (EFSA), Parma, Italy, 2020).

Figures

Figure 1

Examples of published delimiting survey trapping grids for: (a) the leek moth, with a uniform trap density, and (b) the Medfly, with variable trap densities (CDFA, 2013). Each cell represents 2.6 km² (one square mile); the number in each cell shows approximate trap density (no. per km²), and each color indicates a band

Figure 2

Examples of perimeter designs for band contribution and containment testing. (a) Contribution test of Band 3 of the Medfly design with $\rho = 9.7$ traps per km²; (b) Containment testing grid for the leek moth design with $\rho = 13.9$ traps per km². Each cell is 2.6 km², blue circles represent traps, and red crosses indicate outbreak locations

Figure 3

Mean probability of capture for the leek moth grid across different densities. The default density is shown by the solid bar

Figure 4

Probability of capture for the entire 14.5-km grid for Medfly across different trap densities in either (a) the core, or (b) Band 2. Densities in other bands were held constant at default values. Solid bars show default values for that band

Figure 5

Examples of improved designs for delimiting surveys. (a) A 3.2-km diameter circular design for leek moth with 9.7 traps per km^2 . (b) A 4.8-km diameter circular design with 38.6 traps per km^2 in the core and 9.7 traps per km^2 for Medfly