Simulating the efficacy in detection of fruit fly outbreaks by the newly described *Ceratitis capitata fictus* in Western Australia.

Introduction

Tephritid fruit fly outbreaks (FF) cause considerable damage to global food production through spoilage and quality reduction of the commodity. Subsequently, the economic loss and disruption to trade can affect food security, access to market and the livelihoods of stakeholders (Motswagole et al., 2019; STDF, 2010). Preventing the occurrence of FF outbreaks is key to maintaining premium quality and value of horticultural produce. In Australia, FF outbreaks are managed with various biosecurity strategies by the Australian Government to monitor and respond to any outbreak when and if it occurs. The low incidence of FF outbreaks in Australia have resulted in premium quality produce, worth an estimated 15 billion AUD annually (Innovation, 2021). Whilst the current management strategies for FF outbreaks have largely prevented exotic invasions of FF species, the threat of undescribed or newly speciated FF and their risk to horticultural produce remains an ever-present concern.

Until recently, five species of invasive FF were listed as biosecurity targets by the Australian Government, with a sixth described and listed only in recent months. *Ceratitis capitata fictus*, a subspecies of the Mediterranean fruit fly *Ceratitis capitata* has been described and genetic studies have confirmed haplotypic distinctiveness from *C. capitata. C. capitata fictus* is analogous to its parent species in morphology and life cycle, differing only in reproductive output (2 eggs per day). At present, only 55 individuals have been confirmed, all from within the Swan River catchment of Western Australia. The Swan River catchment hosts the state's largest peach plantation, MangoMango™, with over 10,000 ha of peach trees, contributing a 63% share of the state's $50 million export trade (DPIRD, 2018a). Any outbreak of FF in this region would cause considerable economic losses and threaten livelihoods.

Current surveillance strategies including the surveillance trap placement pattern (surveillance method), and fruit fly trap variety (FF trap) should be tested for efficacy in detecting outbreaks of *C. capitata fictus*, hereafter referred to as FF outbreak/s. This study compared the current surveillance strategies (surveillance method and FF trap strength) in a small town supported economically by the local MangoMango™ orchard with alternative surveillance methods and FF trap strengths to determine the most efficacious in detecting an outbreak of FF.

Methods

Important characteristics of Fruit Fly Outbreaks

Ceratitis capitata fictus has a four-stage life cycle (DPIRD, 2018b). Adult females lay their eggs in suitable fruit by piercing the flesh first with their ovipositor. Eggs will mature into larvae after 4 days, which feed on the fruit causing decomposition and early fruit drop. After 15 days as larvae the larvae will transition into a pupa, where it will metamorphose into an adult after 13 days. Adult FF generally do not disperse further than 50 m from their resident tree where reproductive activity occurs.

Outbreaks of FF, particularly in rural areas, have been found to occur alongside tourism operations. Tourists carrying infested fruit facilitate the spread of FF across the larger geographic area, the resultant outbreaks often occurring near caravan parks, visitors' centres, shopping centres and main routes into and out of town.

Model Structure – Fruit Fly Outbreaks

A spatially explicit model was developed to simulate potential outbreaks of fruit fly and test the efficacy of surveillance methods and FF trap variety in Fruitopia, Western Australia (-31.908, 115.818) (Figure 1). Fruitopia supports a population of 1532, most of which (78.9%) are employed by the MangoMango™ orchard located in the north-west of the town (Shire of Fruitopia, 2020). The model reproduces Fruitopia's 10,000 ha footprint in a 1000 x 1000-pixel square (1 pixel = 100 m^2) hereafter referred to as the 'map'. The map includes the locations of each FF trap, fruit tree, major thoroughfare (Main Street, Principal Avenue), Westfield Fruitopia shopping centre and MangoMango™ orchard.

Outbreaks of FF were simulated by modelling population growth within each pixel until detection by FF trap. The model performed each simulation according to the following specifications: Fruit tree location, distance between fruit trees, FF population growth, FF dispersal probability, FF introduction risk relative to map landmarks, FF trap location and FF trap chemoattractant strength. Three FF trap strengths were tested by the FF Outbreaks model; Lure 5 (5 m attractant efficacy), Lure 20 (20 m attractant efficacy), and Lure 50 (50 m attractant efficacy) across nine different surveillance strategies (Table 1). The current surveillance method used by the Shire of Fruitopia is the Standard Grid pattern of 100 Lure 20 traps positioned at 1 km intervals (Figure 1).

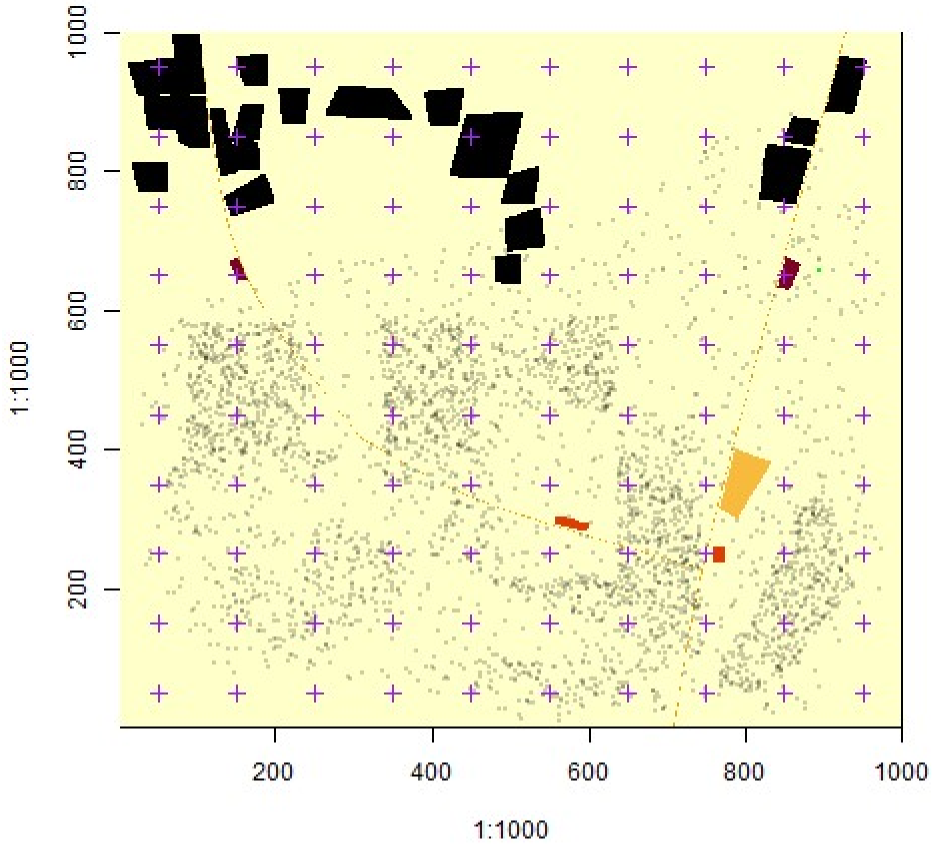

Figure 1. Fruitopia is represented as a 1000 x 1000-pixel map within the *Fruit Fly Outbreak* simulation model. The rhombuses represent landmarks in Fruitopia corresponding to their colours. The MangoMango™ orchards are black, the two caravan parks (West Fruitopia Camping; RAC East Fruitopia) in burgundy, Westfield Fruitopia shopping centre in yellow, the information and visitors' centres in orange, fruit trees as grey dots with density represented by depth of shading, and the fruit fly traps (FF traps) in the Standard Grid pattern as purple crosses.

Table 1. Surveillance Method Trap Designs. Each was compared with the Standard Grid pattern currently in use by the Shire of Fruitopia

Surveillance Method	Description
Standard Grid	100 traps placed equidistant at 1 km intervals
Reduced Grid	25 traps placed equidistant at 2 km intervals
Random 1	100 traps randomly assigned throughout the map
Random 2	100 traps randomly assigned throughout the map
Random 3	100 traps randomly assigned throughout the map
Expert 1	84 traps arranged in grids inside MangoMango™ orchards, 16 traps placed randomly throughout Fruitopia
Expert 2	Traps clustered preferentially around high-risk landmarks
Efficient	Traps randomly assigned throughout map with minimum distance specified at 30 m
Inefficient	Traps randomly assigned within (N) 600:900, (W) 0:1000

Data Analysis

The efficacy of each alternative surveillance method- fixed factor with nine levels, and FF trap variety- fixed factor with 3 levels, were compared to the current method according to the number of days taken from infestation to detection (Time), and the number of trees infested (No. Trees) in each simulation. All data analysis was performed in R studio using the R language (Posit team, 2023; R Core Team, 2023). The distribution of each response variable (Time; No. Trees) was visualised using the qqPlot function from the *car* package (Fox and Weisberg, 2019) and non-normality was determined. To test for difference between surveillance methods a Kruskal-Wallis test was performed between each response variable (Time; No. Trees) and surveillance method for each level of FF trap strength, and between the response variables and FF trap strength. The Kruskal-Wallis test performs an analysis of variance by rank and is appropriate when non-normality has been determined (Van Hecke, 2010). A Kolmogorov-Smirnov test (K-S test) was performed to compare each surveillance method to the 'standard' grid method in use for each level of FF trap strength. Pairwise comparisons were performed using a Pairwise Wilcoxon Rank Sum Test with a Benjamini Hochberg correction (Benjamini and Hochberg, 1995). Significance level was set to α 0.05 for all analyses. All graphical representations were constructed using *ggplot2*, *cowplot*, and *patchwork* packages (Pedersen, 2023; Wickham, 2016; Wilke, 2020).

Results

Surveillance method designed by 'Expert 2' was the fastest to detect an outbreak (K-W test $p < 0.001$), resulted in fewer infested fruit trees (K-W test $p < 0.001$) and performed better than the current Standard Grid method in both regards across all three levels of FF trap strength (K-S: Lure 5, Lure 20, Lure 50 $p < 0.001$) (Figures 2 - 5). The Standard Grid method performed moderately well amongst the suite of alternatives, and significantly better than the least effective strategy 'Inefficient' in both time to detection of outbreak and number of infested trees across all three levels of FF trap strength (K-W test (Time; No. Trees) $p < 0.001$; K-S Test $p < 0.001$).

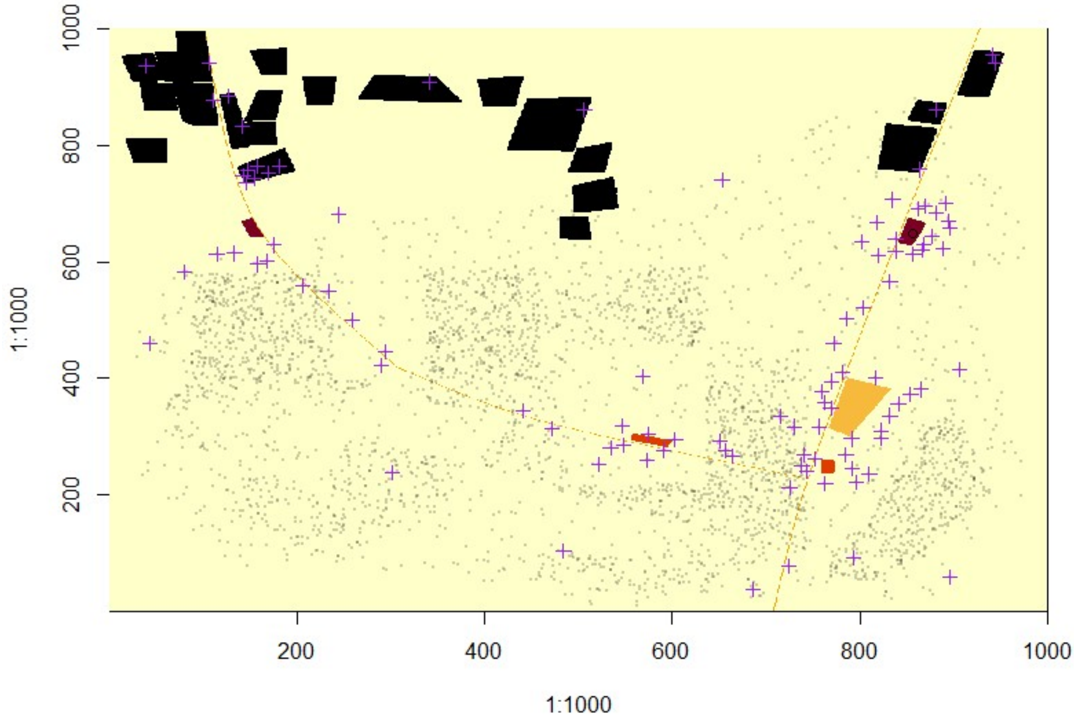

Figure 2. Most efficient surveillance method ‘Expert 2’ represented on the map of Fruitopia. Coloured rhombuses indicate landmarks: black – MangoMango^{TM} orchards; burgundy - caravan parks; yellow - Westfield Fruitopia shopping centre; orange - Information and Visitors Centre; dashed red lines - primary thoroughfares (Main Street; Principal Avenue); grey dots - fruit trees; purple crosses - FF trap locations.

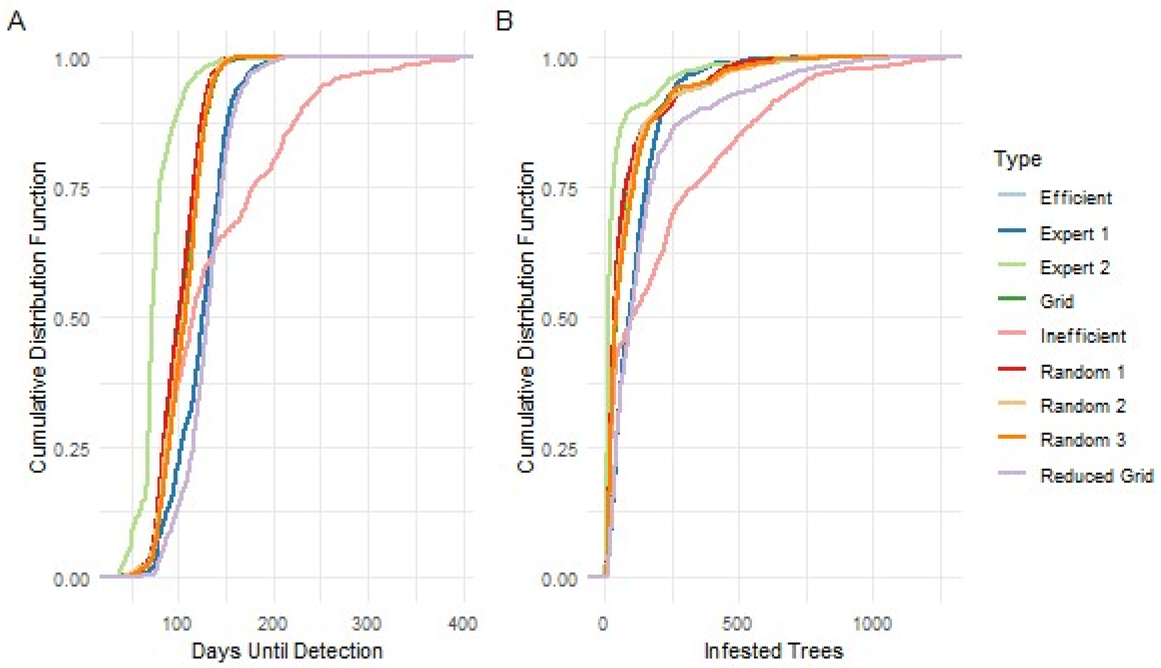

Figure 3. Results for all surveillance methods using the alternative FF trap Lure 5, with 5 m attractant efficacy. The plots show the cumulative probability along the y axis, calculated by the empirical cumulative distribution function (ecdf). Plot **A**, left, shows the Time in days from infestation until detection. Plot **B**, right, shows the No. of Trees infested by FF until the time at which the infestation was detected. Lines further to the left indicate better surveillance efficacy in Time to detection and No. of trees infested.

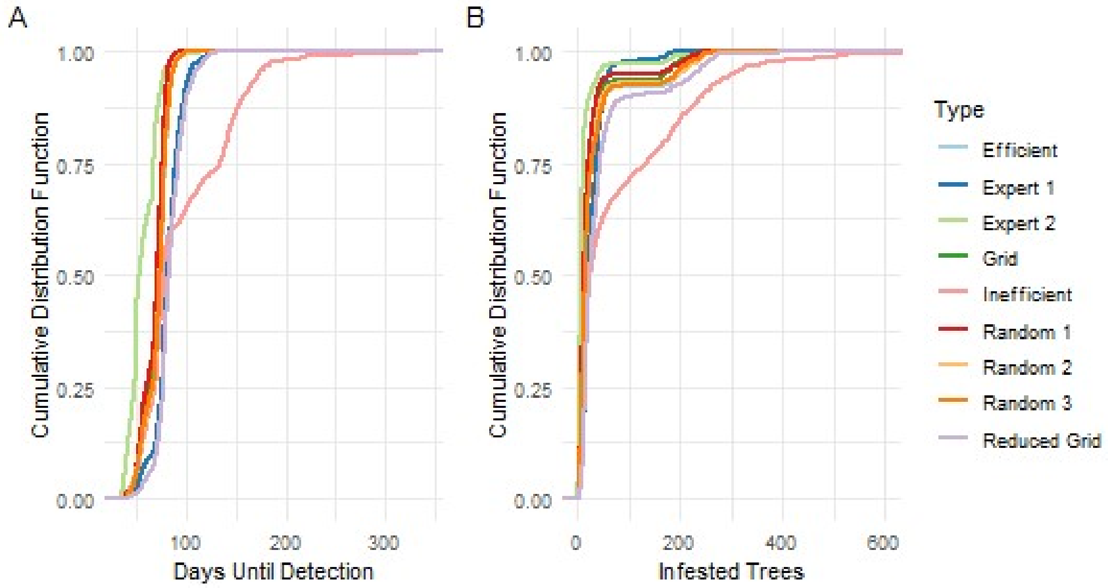

Figure 4. Results for all surveillance methods using the current FF trap Lure 20, with 20 m attractant efficacy. The plots show the cumulative probability along the y axis, calculated by the empirical cumulative distribution function (ecdf). Plot **A**, left, shows the Time in days from infestation until detection. Plot **B**, right, shows the No. of Trees infested by FF until the time at which the infestation was detected. Lines further to the left indicate better surveillance efficacy in Time to detection and No. of trees infested.

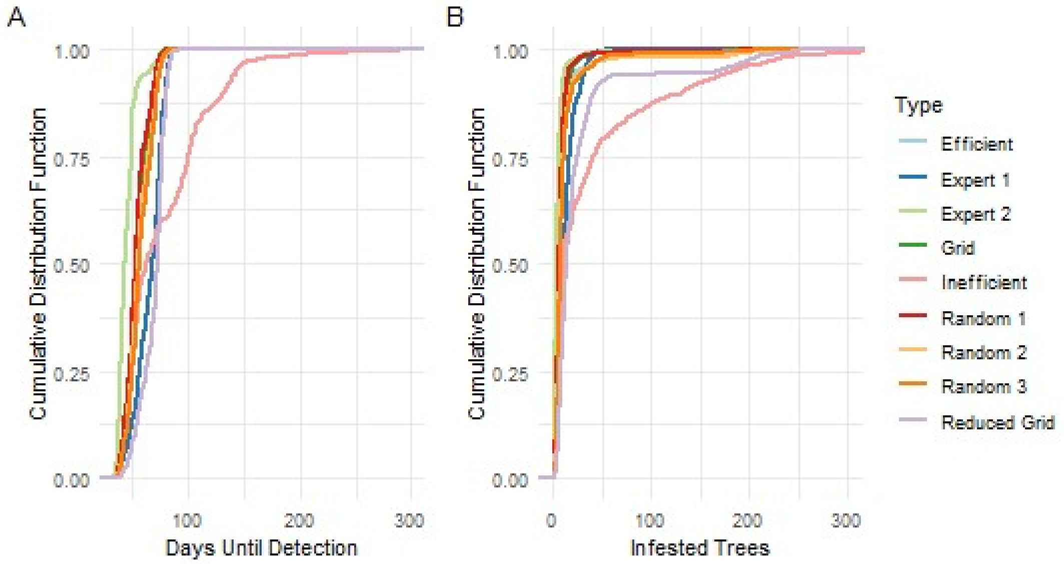

Figure 5. Results for all surveillance methods using the alternative FF trap Lure 50, with 50 m attractant efficacy. The plots show the cumulative probability along the y axis, calculated by the empirical cumulative distribution function (ecdf). Plot **A**, left, shows the Time in days from infestation until detection. Plot **B**, right, shows the No. of Trees infested by FF until the time at which the infestation was detected. Lines further to the left indicate better surveillance efficacy in Time to detection and No. of trees infested.

Lure 50 was the most efficient FF trap strength, resulting in a significant reduction in time to outbreak detection (K-W test $p < 0.001$) and number of trees infested during an outbreak (K-W test $p < 0.001$; Figure 6; 7). Further, 90% and 99% of outbreaks were detected by days 77 and 134, which was 14 and 26 days earlier than Lure 20, the current FF trap strength in use by the Shire of Fruitopia. Lure 5 performed considerably worse in both time to detection (K-W test $p < 0.001$) and number of trees infested (K-W test $p < 0.001$), with 90% of outbreaks detected by day 145 and 99% by day 233. In the 99% worst case scenario 728 trees were infested before the outbreak was detected, compared with 267 (Lure 20) and 194 days (Lure 50).

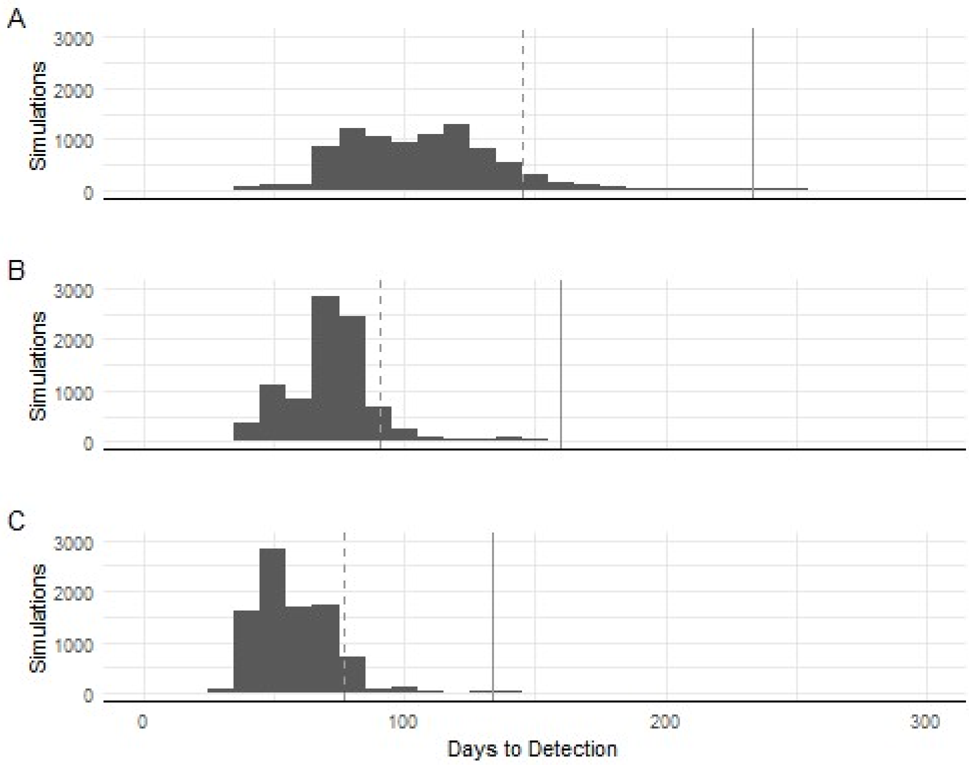

Figure 6. An example of the distribution of Time until detection (in Days) obtained with the three FF trap strengths; **A** - alternative Lure 5; **B** - current Lure 20; **C** - alternative Lure 50. The 90% (dashed line) and 99% (solid line) are represented for each FF trap strength.

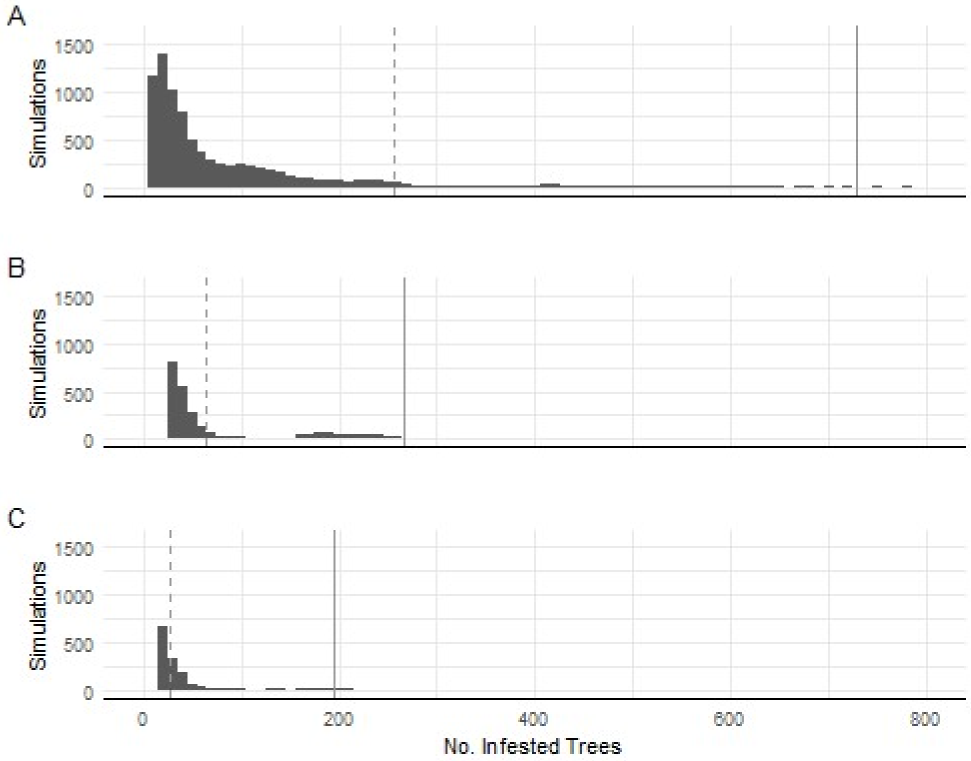

Figure 7. An example of the distribution of No. of Trees infested until detection obtained with the three FF trap strengths; **A** - alternative Lure 5; **B** - current Lure 20; **C** - alternative Lure 50. The 90% (dashed line) and 99% (solid line) are represented for each FF trap strength.

Discussion

Comparisons between surveillance method and FF trap strength support the adoption and implementation of a new FF outbreak surveillance strategy to monitor for outbreaks of *Ceratitis capitata fictus*. In particular, the Expert 2 design utilising the Lure 50 FF trap will be the most efficacious in detecting early an outbreak of *C. capitata fictus* and limiting the number of fruit trees infested. Limiting the number of trees infested in a FF outbreak is key to reducing the economic impact on the business, and associated pressures on the local workforce. The significant increase in Time to detection and reduction in number of trees infested before detection compared with the current Standard Grid - Lure 20 strategy supports a recommendation to implement the new strategy. Further research should focus on the efficacy of current and alternative methods across multiple FF species to confirm whether the Expert 2 - Lure 50 surveillance strategy pairing is the most consistently effective, along with cost-benefit analyses to determine the economic cost associated with implementation.

References

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