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Spatial analysis of mass trapping: How close is close enough ?

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Running title: Evaluating mass trapping attractants

Abstract

BACKGROUND: The identification of new attractants can present opportunities for developing mass trapping, but standard screening methods are needed to expedite this. We have developed a simple approach based on quantifying trap interference in 4×4 trap arrays with different spacings. We discuss results from sex pheromones in Lepidoptera (lightbrown apple moth, *Epiphyas postvittana*), Diptera (apple leafcurling midge, *Dasineura mali*), and Homoptera (citrophilous mealybug, *Pseudococcus calceolariae*), compared with a kairomone for New Zealand flower thrips (*Thrips obscuratus*).

RESULTS: The 25:1 ratio of catch in corner to centre traps observed at 750 *D. mali* traps/ha was still evident as ~5:1 at 16 traps/ha, suggesting trap interference even at such low trap densities. Trap competition for sex pheromone lures at close spacing (<5 m) was evident in 16 trap arrays of the *Pseudococcus calceolariae*, but less so for *Epiphyas postvittana*. No trap competition was observed at 4 m spacings with the kairomone for *T. obscuratus*.

CONCLUSIONS: The ratio of catch in traps in the corner : centre of a 16 trap array at different spacings offers a rapid preliminary assessment method for determining potential for mass trapping. Additional knowledge of vital rates and dispersal is needed for predicting population suppression. Our approach should have value in mass trapping development.

Key words: mass trapping, *Epiphyas postvittana*, *Thrips obscuratus*, *Pseudococcus calceolariae*, *Dasineura mali*, pheromone, arthropod, semiochemical, vertebrate

1.0 INTRODUCTION

Insect pest management has benefited from the development of a range of powerful pheromones and other attractants. [1] Attractants have been incorporated into a range of tactics, including mass trapping, lure and kill, and mating disruption; these tactics can play a key role in pest eradication or long term management. [2, 3] Mass trapping and lure and kill methods involve removal trapping (or killing) of a large number of individuals using volatile compounds, and have the greatest potential to suppress low-density, isolated pest populations. [2, 3] A wide range of insect taxa have been targeted by these tactics, including moths, [4, 5] beetles, [6-8] flies, [9, 10] mealybugs [11] and thrips [12].

Many factors have been investigated but the results have not been synthesised into a simple approach to the assessment of new mass trapping or lure and kill systems. Practical factors influencing the outcome have included low efficiency of traps, saturation of traps, low trap selectivity, the frequent low attractiveness of lures, and the need for high trap density and hence high cost. Simulation modelling has shown that lure improvement makes a big difference to success.[13] If simple theory can be validated from the spatial interaction between traps in a simple 4 by 4 array, then it should be possible to derive an estimated point source density where trap competition is greatest. Lure and kill can eventually be expected to reduce costs, since the infrastructure of traps is not needed. In fact, both concepts are also closely related to mating disruption because in all three systems, dispensers are competitive with females.[14] Communication disruption is a component of these tactics where a proportion of females remains unmated because of the effect of false trail following or habituation of males to the odour. When males have been removed as well, this is likely to be more successful, since male recovery and multiple mating can work against mating disruption.[15]

It is difficult to directly know the fate of insects with lure and kill, since point sources releasing pheromone can be disruptive to monitoring traps through point source competition, without causing mortality. [2] In fact, mass trapping can be a useful stepping stone towards a cost-effective control system, since it is possible to determine the number of males that need to be removed in order to achieve a reduction in damage (e.g. [5]). Our recommended approach is to use mass trapping as a research tool to determine the effectiveness of lures and therefore the appropriate density of lures needed to achieve population suppression. The next challenge is to develop lower cost lure and kill systems to reproduce the required specifications more efficiently. Simulation models are a useful tool for identifying other key attributes needed for success in mass trapping. [13, 16]

The key objective of mass trapping and lure and kill is to reduce reproduction by removing enough individuals in the specific control area, [3] which involves: (a) releasing attractants in the target area, (b) using lures that are able to attract insects as well or even more effectively than natural sources of attraction such as calling virgin females, mating aggregations, or food sources, (c) including efficient traps or stations or formulations for killing the attracted insects, (d) using lures and non-saturating traps that are effective during the entire period of adult emergence and mating, and (e) trapping or killing materials and labour cost less than economic benefits from other treatments.Mass trapping has been successfully used to manage even such ubiquitous pests as blow flies. [17] While the identification of new attractants can present opportunities for developing more environmentally-benign pest management tactics, standard methods for assessing the potential of a lure in the context of mass trapping are not available to facilitate this process.

We chose four diverse model systems in different insect orders to explore a standard approach, based on trap competition, to assessing the potential for mass trapping. The sex pheromone of the apple leaf curling midge *Dasineura mali* (Diptera: Cecidomyiidae) was recently identified, [18] and shows promise for monitoring in pest management. [19, 20] The sex pheromone of citrophilous mealybug, *Pseudococcus calceolariae* a vector of grape vine leafroll viruses, was also recently identified and is being examined similarly. [21] A more attractive four component sex pheromone for *Epiphyas postvittana* [22] offered the opportunity to investigate lure strength as a factor affecting trap performance, compared with the earlier two component blend. Peach lactone was recently identified as a new kairomone for *Thrips obscuratus* (Thysanoptera: Thripidae).[23] These four innovations were used to investigate methods to assess potential for mass trapping, and to test a potential rapid assessment approach to semiochemical screening.

We developed a simple theoretical approach, building on the work of earlier researchers, e.g. [24, 25] by quantifying trap competition and overlapping active spaces. We examined levels of trap interference achieved in diverse habitats including apple and peach orchards, vineyards and pine plantations. In each case, we investigated the spatial effects of trap catch using arrays of 4×4 traps to determine trap competition at different spacings and to thereby indicate the potential for mass trapping and surveillance.

Field trials with 500 traps per ha achieved 96% communication disruption of apple leaf curling midge at 1 ha scale, indicating a potentially successful system. [20] Mass trapping experiments revealed very high levels of trap competition, evidenced by sub-sampling using transects of traps from the sides of the plot towards the centre. [26] The high catches on corners and low catches in plot centres led us to the hypothesis that square arrays of as few as 16 traps could be used to measure trap competition by quantifying the difference in trap catches between corner and centre traps. In each 4×4 grid, there are four corner, four centre (=middle), and eight edge (= side) traps. We hypothesized trap competition would lead to a high ratio of catches in corner traps compared to centre ones, and a somewhat lower ratio of corner to edge and edge to centre catches. By replicating grids at different trap spacings, it should be possible to characterise distances affecting trap competition, and ultimately the optimum trap density for mass trapping.

We adopted this approach to trap for lightbrown apple moth in vineyards and pine forests with lures of different strength and composition, and compared the results to control plots from an apple orchard study reported earlier with 16-trap arrays.[27] We also used 16-trap arrays to investigate optimal trap spacing of citrophilous mealybug sex pheromone traps in vineyards. We then calculated the communication disruption as a function of trap spacing for the mealybug and moth sex pheromone cases to generate inferences about mass trapping. Finally, we tested a powerful kairomone-based attractant for New Zealand flower thrips [23] using the same approach in a peach orchard. This was the only kairomone.

2.0 MATERIALS and METHODS

2.1 Trapping theory

We developed a simple model for trap competition with three basic assumptions. First, trappable insects arise (i.e. mature from non-trappable life stages, or simply are present at the time of trap deployment) uniformly across the landscape, the central part of which is trapped. Second, insects may be trapped only if they arise within the "attraction radius", r, of at least one trap. The attraction radius therefore includes the effects of both insect dispersal and the plume characteristics of the lure. Third, insects arising within the attraction radius of more than one trap have an equal probability of being caught in each. (An alternative assumption, that insects arising within the attraction radius of more than one trap are always caught in the nearest one, led to very similar results). With these assumptions, the degree of competition between traps laid out in a square grid depends on the inter-trap spacing d relative to the attraction radius r. Attraction radii do not overlap, so there is no trap competition, when $d/r \geq 2$. Some competition occurs when $d/r < 2$, including competition between diagonally neighbouring traps when $d/r < \sqrt{2}$, and so on (Fig. 1). Successful mass trapping requires that all insects are with the attraction radius of at least one trap (which occurs when $d/r < \sqrt{2}$), but in practice should aim for multiple overlaps between traps (Fig. 1 b or c). Determining the appropriate trap spacing is a key requirement of successful mass trapping.

Depending on spacing, the traps located on the corners of a square grid should experience less competition than those centre traps that are surrounded by many other traps. The smallest trapping design that might allow such an effect to be measured in the field is a 4×4 'mini-grid' of 16 traps (a 3×3 grid is less useful as it has no replication of the centre traps). We used numerical simulation in R,[28] together with a series of inter-related field trials (Table 1) to compare catches in corner, edge and centre traps to infer the attraction radius and thereby the appropriate trap spacing for mass trapping.

2.2 Apple leaf curling midge *Dasineura mali* (Diptera: Cecidomyiidae)

To determine the extent of trap to trap competition by altering trap density, the sex pheromone of *D. mali*, (8Z)-13-acetoxy-8-heptadecen-2-one [18], obtained from the Natural Resources Institute, Chatham Maritime, Kent (UK), was used as the lure in clear plastic oil-based non-saturating Lynfield fruit fly traps. Lynfield traps baited with 2 µg loadings on rubber septa, with vegetable oil as the killing solution.[20]

The experiment was conducted in apple orchards in Hawke's Bay, New Zealand (39.6^{o}S, 176.8^{o}E). Initially, four replicate plots were laid out with 750 traps per ha in 1 ha plots of cv. Pink Lady (n=2), cv. Royal Gala, and cv. Braeburn. Transects of traps were sub-sampled down the plot edges with traps at 0, 25, 40 and 50 m spacings from the corner to indicate corner-edge effects, while edge-centre transects at right angles were conducted at 0, 4, 7, 11 m spacings towards the centre. Randomly-located traps sub-sampled the interior of each plot (n=4 centre traps per plot, >50 m from border). Corner traps were placed in all cases but other transect traps were deployed in a specific pattern in each replicate with two transects of each direction (towards side at and middle at above spacings) present at each orchard. A total of 29 traps was cleared (of 750) in each of four replicate plots. This number was determined as adequate in a related study which indicated sharp boundaries on the edge of plots, with rapid drop in catch inwards. [26]

In order to confirm the effect of mass trapping density on catch per trap, traps were next deployed in four replicate 1 ha orchard blocks at each of three trap densities over a constant area over the same period: 4, 16 and 750 per ha (Table 1). Catches from 7 February to 9 March in four traps within each block were used for comparison between trap densities. A second series of 16 traps in four replicate 1 ha plots was deployed from 24-27 August - 25 October 2007 (1st generation) and 11 December 2007 - 19 February 2008 (3rd generation).[29] These traps (33 m spacing) were designed to produce the corner to centre ratio and edge to centre ratio as above. Traps were operated over the first and much larger third generations in order to determine the reproducibility of the results, in case there was an effect of insect density.

2.3 Light brown apple moth *Epiphyas postvittana* (Lepidoptera: Tortricidae)

The four components of the sex pheromone of *E. postvittana* (*E*)-11-tetradecenyl acetate (E11-14Ac), (*E*,*E*)-9,11-tetradecadien-1-yl acetate (E9E11-14Ac), (*E*)-11-tetradecen-1-ol (E11-14OH), and (E)-11-hexadecenyl acetate (E11-16Ac) (ratio 95:5:1:0.5) [22] were obtained from Plant Research International, Wageningen, The Netherlands. Lures were either prepared as a two component blend [30] or four component blend [22] applied to red rubber septa (West Pharmaceutical Services, Kearney, N.E., USA) in 200 µl of n-hexane GR (Merck Ltd, Auckland, New Zealand). The solvent was evaporated in a fume hood and the septa were stored in heat-sealed foil bags at -20ºC until ready for use.

The two component pheromone [30] was deployed at 10.5 and 105 μg loadings on rubber septa in red delta sticky traps operated for six weeks from 2 November 2006 until 11 January 2007, in a *Pinus radiata* plantation forest in Canterbury, New Zealand (Lat 43.5° S, Long 172.4° E) (Table 1). Traps were deployed in 16 trap arrays at spacings of 2, 4, 8, 16 and 32 m, replicated five times (400 traps for each lure). The catch from the greatest trap spacing distance was used for comparison of the effects of competing traps on communication disruption (i.e. assumed to be zero at 32 m for the four central traps). In the third case, we used the more active four component pheromone, [22] deployed at 1 mg loading on rubber septa in red delta sticky traps in 16 trap arrays operated for six weeks from 12/11/2012 to 7/1/2013 in a vineyard in Canterbury, New Zealand at spacings of 2, 4, 8, 16 and 32 m (Lat 43.4° S, Long 172.4°E) (Table 1). These data were compared with corner to middle ratios calculated from total catch results from three replicate 16 trap arrays operated in an untreated apple orchard from 16 March - 25 May 1994. [27]

Table 1

2.4 Citrophilous mealybug *Pseudococcus calceolariae* (Homoptera: Coccoidea)

The racemic sex pheromone of *Pseudococcus calceolariae*, chrysanthemyl 2-acetoxy-3-methylbutanoate[21] was obtained from Jan Bergmann (Instituto de Química, Pontificia Universidad Católica de Valparaíso, Avda. Brasil 2950, Valparaíso, Chile). It was loaded at 2 μg per rubber septum and deployed in red delta sticky traps operated in Hawke's Bay, New Zealand vineyards (39.69° S and 176.92° E) in 4 × 4 trap arrays at four spacings (Table 1): 8 × 8 m between traps (0.0256 ha), 16 × 16 m (0.1024 ha), 32 × 32 m (0.4096 ha) and 64 × 64 m (1.64 ha), each replicated four times (256 traps in all). The catch from the greatest trap distance was used for comparison of the effects of trap interference (assumed to be zero at 64 m). Traps were checked and counted weekly from 11 February to 8 March 2011.

An extension of the trial with the same method used spacings in the array of 1.6, 3.2 and 6 m. Traps were deployed from 23 February to 3 April 2012. The corner to centre ratio data were found to be continuous again as expected since the ratio is independent of density, and the two data sets were therefore considered together.

2.5 New Zealand flower thrips, *Thrips obscuratus* (Thysanoptera: Thripidae)

The 6-pentyl-2H-pyran-2-one (96 %), was obtained from Sigma-Aldrich Chemical Company (St Louis, MO, USA). It was dispensed into polyethylene bags (500 mg).[23, 31] The catch in red delta traps was recorded in a peach orchard (‘Yumyeong’) near Lincoln, Canterbury (43.6°S, 174.48°E) over 1 wk in February 2010. Three replicate blocks of 16 trap arrays were operated at the distance between traps of one tree row spacing (4 m). Fruit were present but unripe (~4 weeks to harvest) and unattractive to thrips. [23]

2.6 Statistics and modelling

Regression of catch on trap density was done after pooling the data for each time interval for each trap. Catch in the corner, edge and centre traps were compared to determine whether significant spatial effects were present. Ratios of trap catch were calculated on pooled data. Percentage disruption of communication was calculated for each distance as 100 - 100 × (catch in centre set 4 traps at a given distance/catch in centre set of 4 of maximum-spaced traps), where catch in maximum-spaced traps was assumed to be without trap competition. This assumption was tested from graphical comparison of the ratio data with distance. Catches were normalized to relative trap catch for the appropriate corner or side trap in each transect, and the values used in regression with distance, due to population size variation.

3.0 RESULTS

3.1 Predicted patterns

The model (Supplementary Material) suggests that once the attraction radii of traps start to overlap (when $d/r < 2$) then trap catches should be depressed, with different rates of reduction for corner, edge and centre traps. For example, when trap spacing is equal to the radius of attraction, centre traps are predicted to capture about a third of the number of that for a non-competing trap, while edge and corner trap catches are just below a half and two thirds, respectively (Fig. 2). Trap catch suppression is predicted to be similar in both large and small grids except when traps are very close to each other (d/r small). This relationship provides one method for estimating the attraction radius and therefore the appropriate trap spacing for mass trapping: complete coverage ($d/r < \sqrt{2}$) requires mass trapping to achieve at least 37%, 27% and 18% suppression in trap catch for centre, edge and corner traps, respectively (Fig. 2).

In addition, the ratios of trap catches in outer versus centre traps are predicted to increase with decreasing trap spacing, because centre traps experience greater competition than those along edges or at corners of the trapping grid. When traps are sufficiently widely spaced that there is no competition ($d/r \geq 2$, Fig. 1A) catches in all traps should be approximately equal. As the inter-trap distance shrinks, corner traps catch relatively more insects than edge traps, which in turn catch more than centre traps, resulting in increasing ratio of trap catches from corner/edge, edge/centre and particularly corner/centre traps (Fig. 2). In large grids, the ratios continue to increase with shrinking trap spacing, but in small grids the ratios decrease again as all traps eventually overlap with all others. In 4×4 minigrids, the corner/centre trap catch ratio is predicted to peak at ≈ 2.62 when $d/r \approx 0.6$ (Fig. 2). This provides a second way to estimate the attraction radius: if the 4×4 minigrid spacing that maximizes the corner/centre ratio is estimated from field experiments as d^*, then the attraction radius can be estimated as $d^*/0.6$, and mass trapping should aim for a trap spacing of not more than $(\sqrt{2}/0.6)d^* \approx 2.3d^*$.

Fig. 2

3.2 Apple leaf curling midge *Dasineura mali* (Diptera: Cecidomyiidae)

A total of 160,031 midges was caught across the four orchards in pheromone-baited oil traps operated at three densities (4, 16 or 750 per ha) from 7 February to 9 March 2007. There was a strong inverse relationship between log trap density and log catch per trap, with the lowest catch per trap predictably evident at the highest trap density (Fig. 3) (r^2= 0.9978). Assuming that there was no trap competition at the widest trap spacing (d = 50 m), then inner trap catch at 23 m spacing was 20% of the value at 50 m. From Fig. 2A, this level of catch suppression in inner traps is expected to occur at relative trap spacing $d/r \approx 0.8$. Knowing d = 23 m, we therefore estimate the attraction radius r as 23/0.8 = 29 m. Similarly, relative trap catch at 3.7 m spacing was 0.9% of that at 50 m, with Fig. 2A suggesting $d/r \approx 0.15$ and therefore r = 3.7/0.15 = 25 m, which is very similar to the value estimated from 23 m spacings.

Fig. 3

At 750 traps per ha, very striking changes in trap catch occurred with trap position from the border into the block (Fig. 4), as expected from a case of high trap active space overlap between adjacent traps (Fig. 1d). Traps on the corner of each plot caught the highest numbers of midges, while intermediate catches were made on the edges of plots, depending on position. Central traps were uniformly low in catch, while edge and corner traps caught the highest numbers (Table 2, Fig. 4).

Fig. 4

Table 2

The 16 trap arrays at 23 m spacing (Fig. 5) were operated in four apple orchards for two generations with different insect densities (Table 2), but as expected there was no significant effect from insect density on the ratio of catch in the four corner to four centre traps; the ratio was 3.5 ± 0.4 (SEM) ($t = -0.25$; $P = 0.815$; df = 5) (based on n=372,988 midges per replicate per generation).

Fig. 5

3.3 Light brown apple moth *Epiphyas postvittana* (Lepidoptera: Tortricidae)

A total of 996, 391, and 1981 moths were caught in the three trials of 16 trap arrays with five trap spacings. There was a peak in the corner to centre ratio at the 8 m spacing (Fig. 6). The peak in ratio was consistent for trials conducted in both vineyard and pine plantation habitats and with different lure amounts and blends (Table 1), however, the magnitude of the peak differed between treatments. The values of corner to centre ratio were consistently highest at all spacings with the most attractive lure (four component, 1 mg loading).The earlier apple orchard results collected as part of another study [27] (n=1,426 moths) were only at a single spacing, but the corner to centre ratio was a close fit to the data generated in the pine plantation with the two lure strengths. From the modelling, this suggests the attraction radius $r = 8/0.6 = 13$ m, and mass trapping should aim for no more than 18 m between traps (Fig. 6).

Fig. 6

3.4 Citrophilous mealybug *Pseudococcus calceolariae* (Homoptera: Coccoidea)

There was a strong spatial effect of trap position on catch below 8 m spacing between traps, with a consistent decline in corner to centre ratio with log distance between traps out to 64 m, where the ratio was close to unity, showing no competition (Fig. 7). There were no cases of empty traps. A total catch of over 533,545 male mealybugs was made, suggesting that the results with ratios should be highly robust. The ratio of catch in corner to centre traps peaked at 3.2 m spacings between traps. The trap spacing can be converted to the number of traps or other type of killing stations needed per ha for best predicted results. The peak in ratio of corner to centre trap catch was equivalent to a trap density of ~1,000 traps per ha, and the trend suggests greater efficacy would generally result with high point source density. It is possible that the assumption of no effect of trap competition at 64 m was violated, which may explain the higher values than expected in the array (due to the difference between 16 and infinite numbers in a grid , which peaks about 3.0 in a 16 trap array). Communication disruption increased with reduced distance between traps, although the results were least dramatic for the moth case (Fig. 8).

Fig. 7

Fig. 8

3.5 New Zealand flower thrips, *Thrips obscuratus*

Despite high mobility and catches that can exceed 9,000 insects per trap at some locations,[32] total catch of 18,665 thrips in this short study, there was no significant effect of corner or centre between catches of thrips in traps in the 16 trap array. This is equivalent to a corner to middle ratio of 1:1 and indicates no trap competition at one tree spacing. Therefore the active space must be closer than the tree spacing, making mass trapping impractical. The mean catch per trap in the week was 393 ± 47.9 (mean ± SEM), and no empty traps occurred.

4.0 DISCUSSION

Our model suggests that the ratio of catch in traps in the corner and centre traps of a 16 trap array offers a simple approach to evaluate the potential for trap interference of novel odourants for a species dependent on inter-trap distance, although other geometric arrangements might also work.[24, 33, 34] For example, a nine trap array has an advantage of using fewer traps but has no pseudoreplicates of the inner traps. For the aforementioned sex pheromone case studies, the corner traps caught more insects than center traps. The effect of trap competition changed with distance and spatial relationship with competing traps. Close spatial arrangements of traps proved very effective at detecting trap interference, although the peak competition distance apparently varied between species. This result, which is expected by our model, indicates the potential of this approach to assess trap competition in a number of ways.

With a high trap density, the pheromone concentration within the plots will have been greater, making it harder for the male moths to discriminate between odour sources until the density of traps decreased or the moths made it to the edge of the array allowing them to find discrete sources [33], or pheromone concentrations may have been so great as to exceed the upper threshold for behavioural response of the moths [35], leading to a depression of catch in the centre traps compared with the corner traps. The assumption of no trap competition at the greatest spacing (64 m for mealybugs and 32 m for moths) enabled the comparison of two of the systems for likely efficacy in mass trapping on a common parameter, *d*. Weak competition may have still been present even at these distances especially when taking into account wind direction, speed and orientation of traps down or across planted rows [34], but this bias is low level and in favour of showing less treatment effect.

In the case of arrays with only 16 traps, the four traps in the centre reveal the greatest effect of trap competition, and it seems that there is a trade-off with efficiency of using such a small grid and consequent loss of scale of effect. The apple leaf curling midge male removal operating at the high trap density with 25:1 ratio of corner to centre catch may have had an advantage in level of communication disruption due to the high number of traps involved. Changing spatial scale can affect the level of communication disruption due to edge effects.[36]

The method used for the mealybug and moth, with 16 traps at a series of spacings, was less trap intensive than with the midges (750/ha). In comparison, communication disruption of the mealybug reached higher levels than with the moth, independent of lure. For the moth, a more attractive blend (4-component at 1 mg loading) did not materially change the outcome of communication disruption with distance than the less attractive two component cases at 10.5 or 105 µg loadings, but the ratio values were higher with the four component pheromone. The attraction radius of the pheromone-baited moth traps was estimated from the model at 13m. It was assumed that all insects were arising in the plot and once inside the attraction radius of a trap would be trapped, although the probability of being trapped may be related to the distance from the attractant once within the area of influence [24, 37]. The moth data showed that the peak of the ratio of corner to centre traps occurred at 8m, even though different lure strengths and blends of pheromones were used (Fig. 6). The increased corner to centre ratio in the 4-component, 1mg loaded lures probably represents an improved probability of catch in a trap once a moth was within the attraction radius. Corner traps had less competition from neighbouring traps, thus an improved catch probability would lead to the observed difference in the ratio of catch to centre traps than a less effective lure at the same distance between traps. Had the attraction radius increased with lure strength, then we would have expected to see a corner to centre ratio peak at a distance greater than 8m with the stronger lure.

Close range behaviours may have contributed to the difference between the model predictions and some insect catches at close spacings (e.g. moth cases). The phenomenon of trap competition that was visible for *D. mali* in a mass trapping plot at 1 ha scale, with high catches in corner traps (peaking at 25-fold for corner to centre ratio) was successfully reproduced in much smaller grids of only 16. The change to 16 trap arrays reduced this ratio to five-fold, but provided a potentially significant saving in traps in determining the effect.

The 16-trap array system proved capable of identifying two cases (*D. mali* and *P. calceolariae*), where mass trapping should lead to strong performance at suppression, based on the ratio of catch in the corner to centre traps. The approach showed the effects of changes in either trap spacing or density over a fixed area, which caused a drop in grid efficiency with increase in *d*, the distance between traps. Improvements in efficacy of control could result from a decrease in spacing distance *d*, or an increase in *r*, the radius of attraction of individual traps, since the goal is to maximise overlap between traps or killing stations, in the case of lure and kill systems. [2]

The transects into the treated area with traps for *D. mali* at 3.7 m spacings showed a rapid change in catch with a short distance, with communication disruption evident from reduced catches in the central area of the treated blocks. This transect-based approach represents one method of determining potential effects from mass trapping or lure and kill. [38] Suppression of *D. mali* appears promising from these tests but other factors can be very important to the outcome, such as multiple mating by males, which is known to be an issue because it dilutes the population suppression effect from a reduced impact in the mating rate of females. [20] High density and reproductive rate as well as female dispersal into the plots at 750 traps/ ha likely led to shoot damage reductions of only by ~50%, [26] which supports the need for area-wide treatment. Treating larger areas with male removal should solve immigration problems.[39]

For the citrophilous mealybug, *P. calceolariae*, further investigation of mass trapping or lure and kill systems appears warranted, although the optimum spacing is likely to need to be close and up to 1,000 points per ha may be needed for optimum results at high insect density. This is likely to require the development of different technology for control, offering cost-effective delivery of high point source density. It is likely that the efficiency of synthetic pheromone will be competitive with females due to longer hours of release for the synthetic lures than for the female.[21] Consideration of multiple mating needs to be made in future assessments of population reduction in this species.

Mass trapping of tortricid moths has been attempted previously using sex pheromone on several species, with the best results from high density trapping. [4, 15] In the case of *E. postvittana*, the lure strength was shown to have a major role to play in determining trap and grid efficiency, assessed as the corner to centre ratio. A new four component blend [22] was the most attractive lure and had the highest ratios of corner to centre, but lure strength and components did not affect the distance for maximum trap competition, at 8 m. Comparison of communication disruption from trap interference experiments suggested that spatial effects were possibly performing differently in the moth case compared with the mealybug. There was a tendency for trapping in central traps to coalesce. It is known that tortricid moths will track upwind lures in sequence [33], but it is not known how an array of competing traps are perceived by such moths. Our results suggest that this may indicate greater difficulty in achieving success with mass trapping of moths, although dispersal distance is also likely to be important. In practice mating disruption is already available, and mass trapping is not widely used against Lepidoptera, although there have been many tests.[40]

For the case of the flower thrips, we are reporting negative results with our trapping array experiment, despite hundreds of catches in each trap. The lack of evidence for trap competition at one tree spacing offers little hope for mass trapping of this species with a kairomone, and potentially shows how the system can be used to screen prospective alternative lures. This negative result does not rule out other IPM strategies using the new kairomone [31] but the sheer abundance of this highly mobile pest presents very significant challenges.

Communication distances, like atmospheric pheromone concentration studied in mating disruption, will vary as a function of wind speed, vertical leaf area density, canopy form and other factors, [41] but recent evidence suggests that plant volatiles can operate over attraction distances as much as 8 m, as in the case of a range of arthropod taxa in soybeans.[42] Several authors have considered adequate separation to avoid interference between such plant volatile treatments to be between 10 to 35 m. [43-45] For sex pheromones, inter-trap communication distances of up to 80 m were recorded for gypsy moth in forest under light wind speeds, using 6 by 6 grids of traps, which showed lower catches in the centre of the array. [46] In another study with a forest system, effects were seen at even greater distances. [47] Bark beetles trapped with pheromones in 7×7 trap arrays showed higher catches on corners in many plots [48] similar to the results seen here, and apparently predictable by the geometry as in our case with the 4×4 array. In an open field situation with Oriental fruit moth, active flight distances of up to 80 m were observed to a sex pheromone lure[35], and for *Cydia nigicana* the attraction range of males to their sex pheromone was estimated at 200 m with stimulation (response to but not necessarily directed movement towards the odour source) from 400 m away.[49] These values suggest that our estimates of the maximum distances with nil effect at 32 or 64 m may be underestimates, rendering our estimates of communication disruption also underestimates.

The use of 16-trap arrays to determine whether there is a pattern of higher catch in the corners of the block is a relatively easy process, although the size of the ratio between catches in corner and centre traps was reduced in this array compared with the plots with high trap density. The size of the ratio also varied with species, trap density and pheromone loading.

Future assessments of the potential for mass trapping of new semiochemicals could follow a simple protocol of testing for trap competition at four or five spacings, and compare the corner to centre ratio to determine the optimum spacing. The edge to centre ratio is logically less sensitive than the corner to centre ratio but may have other advantages in calculating the active space of traps.

More work is needed to determine guidelines for estimating values for these ratios, but the corner to centre ratio and the determination of a peak in this parameter at a certain trap spacing would appear to represent a useful basis for optimising spacing. Trap competition was clearly a spatially determined phenomenon, since apple and peach orchard, vineyard and forest habitats were employed in the various trials and the effect was apparent in all ecosystems.

The greater communication disruption achieved with the mealybug sex pheromone mass trapping trials compared with the moth case suggest that this tactic may have better promise against the mealybugs. The lack of any trap competition present in the case of New Zealand thrips in a peach orchard suggests that cases that fall into this category may not be suitable for mass trapping.

It is worth briefly considering the possible extension of our approach to derive estimates of trap efficiency and optimal spacing of equivalent killing systems to vertebrate pests. In fact, there are similarities between mass trapping of insects and trapping or poisoning of vertebrates. Poisoning has been widely used to eradicate pests such as rats on islands. [50] The similarity is most obvious with ground-based operations, with regularly-spaced stations. For example, ground treatment for *Rattus rattus* in New Zealand’s Pureora Forest used brodifacoum at 31 m spacings, with an 8×8 grid arrangement.[51] Unfortunately, spatially explicit records are not available, so any effects of trap competition on the corner or middle positions cannot be assessed for this case, but other records likely exist with vertebrates that could be analysed spatially. Subsequently, aerial operations have predominated in such forests, [51] where access can be difficult due to terrain, so data collection of this type was prevented. One recent New Zealand operation targeted removal of 13 invasive mammal species, [52] relying heavily on aerial methods. However, ground-based removal of cats (*Felis catus)* has been successful on a Mexican island [53] with bait stations at 20 m intervals after tracks were cut. It is possible that our approach to mass trapping, developed cost-effectively with large data sets for insects, may offer useful ideas for vertebrate pests to reduce the cost of developing new odourant-based tools and understanding the effects of spacing.

However, the lessons from failing to eradicate rats in one tropical island case [53] identifies the need to understand the complexities such as relative attractiveness of baits and alternative foods, which can change seasonally. Here, we have developed an approach to determining the potential for novel semiochemicals against arthropods and other targets, as well as the framework for assessing the efficacy of a trapping grid, particularly at high trap densities that could be considered for mass trapping. Further work is needed to determine whether the corner to centre ratio can be developed into a predictive tool for success at mass trapping, as the current work tends to suggest.

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Legends

Figure 1 Theoretical trap framework for assessing trap competition, showing active spaces with a) no overlap, which might be expected in surveillance trapping, b) partial overlap, c), increasing overlap, d) extensive overlap needed for mass trapping.

Figure 2 Predicted changes in trap catch (top) and trap catch ratios (bottom) in (a) full sized and (b) 4×4 arrays as trap spacing *d* varies relative to the radius of attraction *r*. Vertical lines denote the maximum trap spacing compatible with mass trapping.

Figure 3 Mean catch per trap of male apple leafcurling midge *Dasinuera mali* in 1 ha apple orchard plots (n=4), at three densities of oil-filled plastic Lynfield traps baited with sex pheromone, with 4, 16 or 750 traps per ha.

Figure 4 Mean catch per trap of male apple leafcurling midge *Dasinuera mali* in 1 ha apple orchard plots (n=4), with 750 oil-filled plastic Lynfield traps baited with sex pheromone per ha and sub-sampled spatially as shown.

Figure 5 Mean catch per trap in a labour-saving array with a 4 x 4 array of sex pheromone traps for apple leafcurling midge (*Dasinuera mali*), at 25 m spacing in 1 ha apple orchard plots (n=4).

Figure 6 Relationship between trap spacing and the ratio of corner to centre catch in arrays of 16 traps of light brown apple moth, *Epiphyas postvittana* with two component (at 10 or 100 µg) or four component blends (at 1 mg) of female sex pheromone. The apple orchard data (triangle) were first reported in another study.[27]

Figure 7 Pheromone trap competition in citrophilous mealybug *Pseudococcus calceolariae* from corner to centre traps in an array of 16 traps at different spacings in vineyards in Hawke’s Bay, New Zealand, expressed as inter-trap spacings. Line is best fit by least-squares regression.

Figure 8 Communication disruption as a function of trap spacing in citrophilous mealybug *Pseudococcus calceolariae* and light brown apple moth, *Epiphyas postvittana*, calculated from four centre traps in a replicated 16 trap array at each distance. Lines show best fit by least-squares regression.

Tables

Table 1. Trap spacing and other parameters used for comparing trap competition to assess potential for mass trapping, using trap arrays with insects from three different orders.

Insect species (Order: Family)	Crop	Experiment/ spacing (m)	Number of traps per plot	Lure and trap type
Apple leaf curling midge *Dasineura mali* (Diptera: Cecidomyiidae)	Apple orchards	Expt. 2.3.1: 3.7, 23, 50 m	750, 16, 4	2 μg of sex pheromone (8Z)-13-acetoxy-8-heptadecen-2-one[18], septa in oil traps[20]
..	..	Expt. 2.3.2	16	..
Light brown apple moth *Epiphyas postvittana* (Lepidoptera: Tortricidae)	Pine plantation	Expt. 2.5.1: 2, 4, 8, 16, 32 m	16	10.5 and 105 μg, (E11-14Ac/ E9E11-14Ac) [30], septa in sticky traps
..	Grape vines	Expt. 2.5.2: 2, 4, 8, 16, 32 m	16	1mg, (E11-14Ac/ E9E11-14Ac/ E11-14OH /E11-16Ac), septa in sticky traps[22]
..	Apple [27] orchard	17.6 m	16	105 μg, (E11-14Ac/ E9E11-14Ac)[30], septa in sticky traps
Citrophilous mealybug *Pseudococcus calceolariae* (Homoptera: Coccoidea)	Grape vines	Expt. 2.4.1: 8, 16, 32, 64 m	16	1 mg, chrysanthemyl 2-acetoxy-3-methylbutanoate, sex pheromone [21], septa in sticky traps
..	..	Expt. 2.4.2: 1.6, 3.2, 6 m	16	..
New Zealand flower thrips *Thrips obscuratus* (Thysanoptera: Thripidae)	Peach orchard	Expt. 2.6 4 m	16	500 mg of 6-pentyl-2H-pyran-2-one, polyethylene bags in sticky traps[23]

Table 2. Effect of corner or edge to centre trap position on mean catch of apple leaf curling midge *Dasinerua mali* (Cecidomyiidae) in a 1 ha block, at two trap densities.

	Trap density	750 traps /ha			16 traps /ha		
Generation		Corner	Edge	Centre	Corner	Edge	Centre
1	Mean midges /ha	9,207	1,843	358	23,600	14,125	4,575
	Ratio of position: centre	25.8	5.2	..	5.2	3.1	..
3	Mean midges /ha				58,541	41,090	22,375
	Ratio of position: centre				2.6	1.8	..

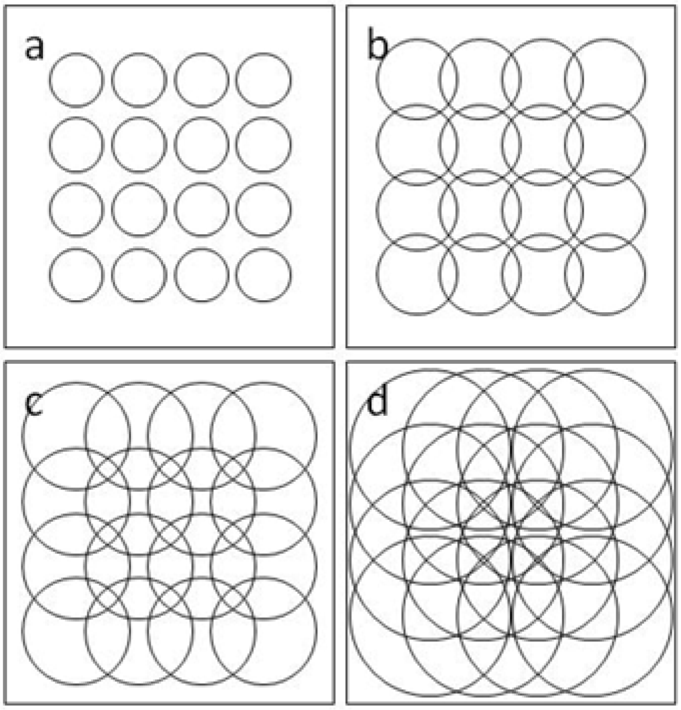


Fig. 1.

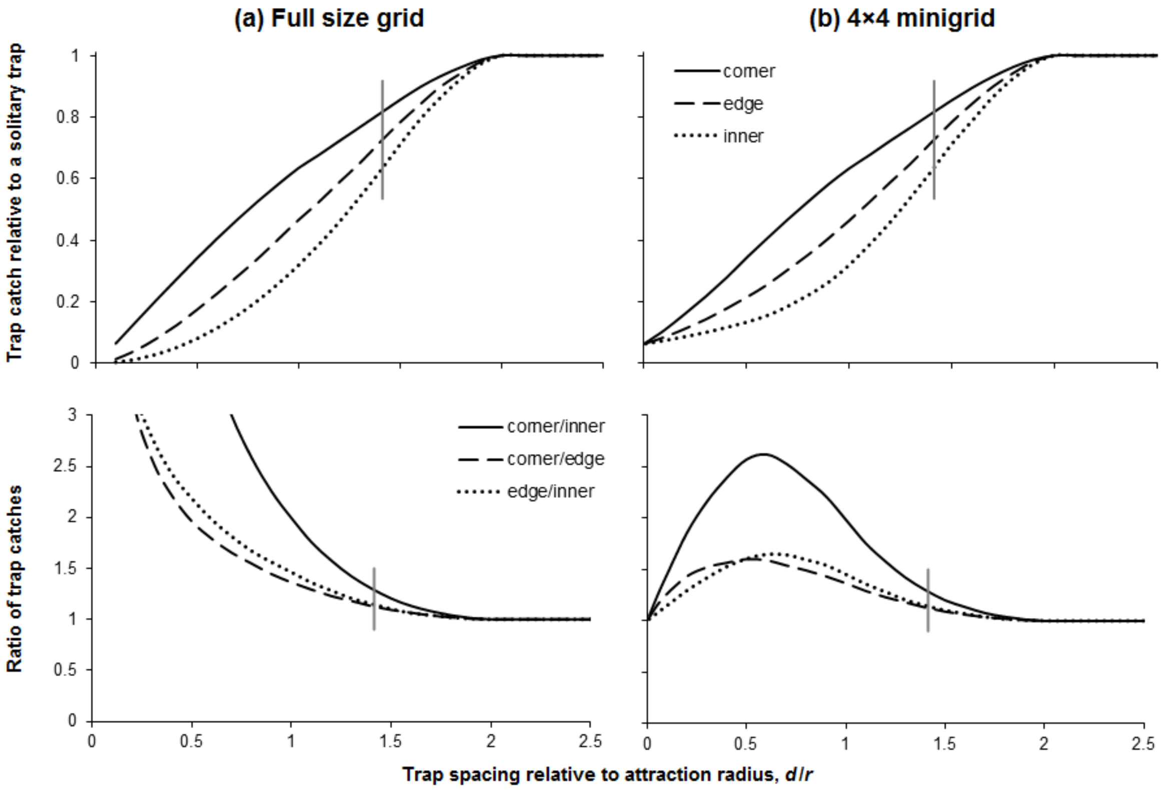

(a) Full size grid
(b) 4×4 minigrid
Trap catch relative to a solitary trap
0
0.2
0.4
0.6
0.8
1
corner
edge
inner
Ratio of trap catches
0
0.5
1
1.5
2
2.5
3
corner/inner
corner/edge
edge/inner
0
0.5
1
1.5
2
2.5
Trap spacing relative to attraction radius, d/r

Fig 2

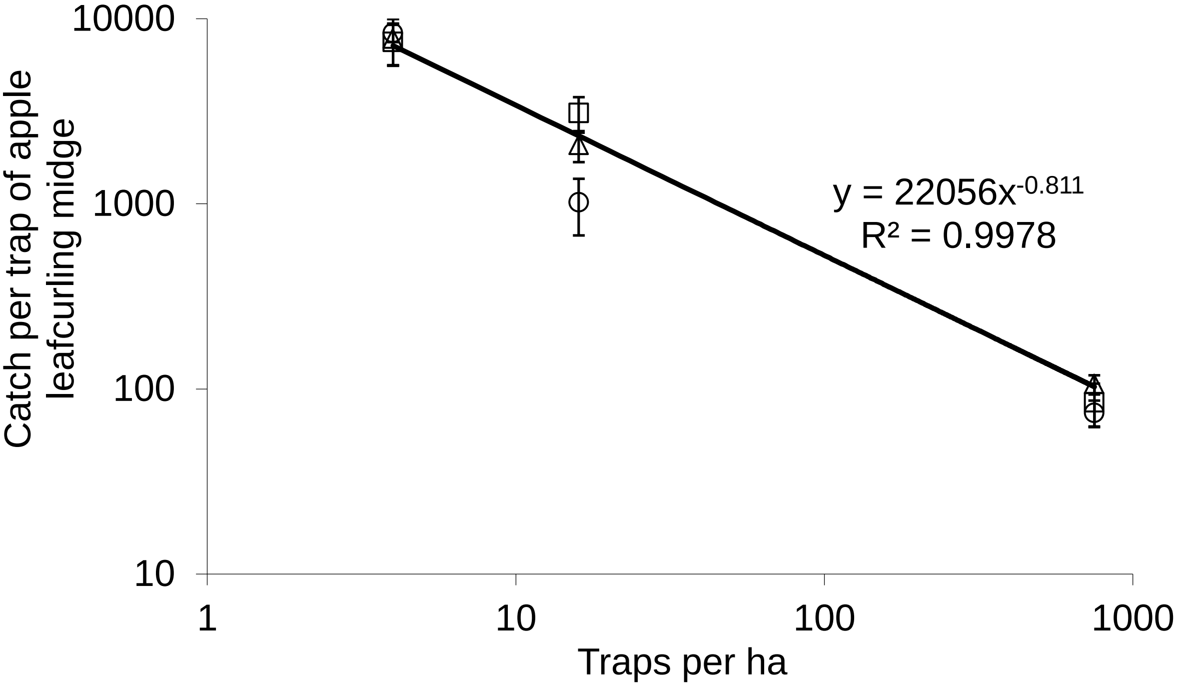

10000
1000
100
10
1
10
100
1000
Catch per trap of apple leafcurling midge
Traps per ha
y = 22056x-0.811
R² = 0.9978

Fig. 3.

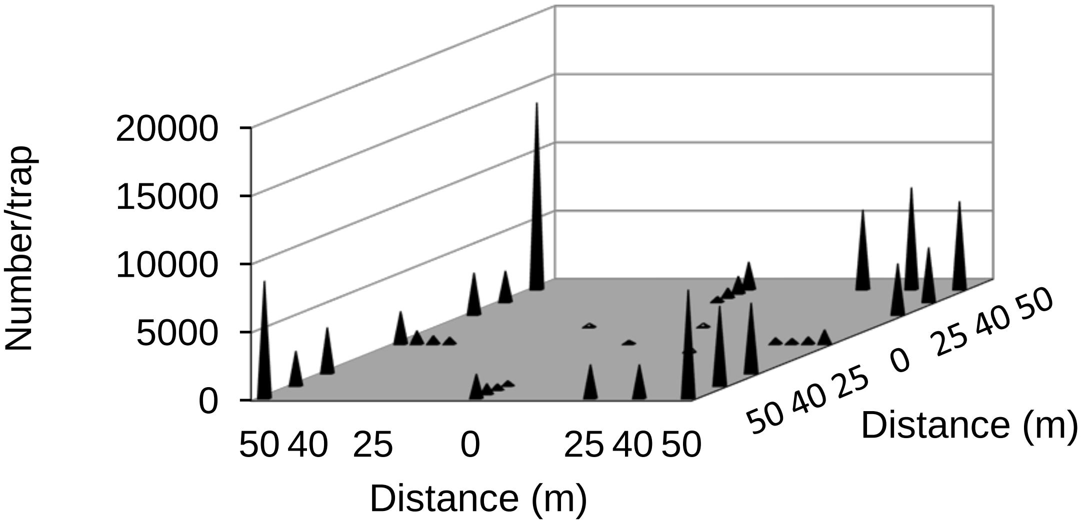

20000
15000
10000
5000
0
Number/trap
50 40 25 0 25 40 50
Distance (m)
50 40 25 0 25 40 50
Distance (m)

Fig.4

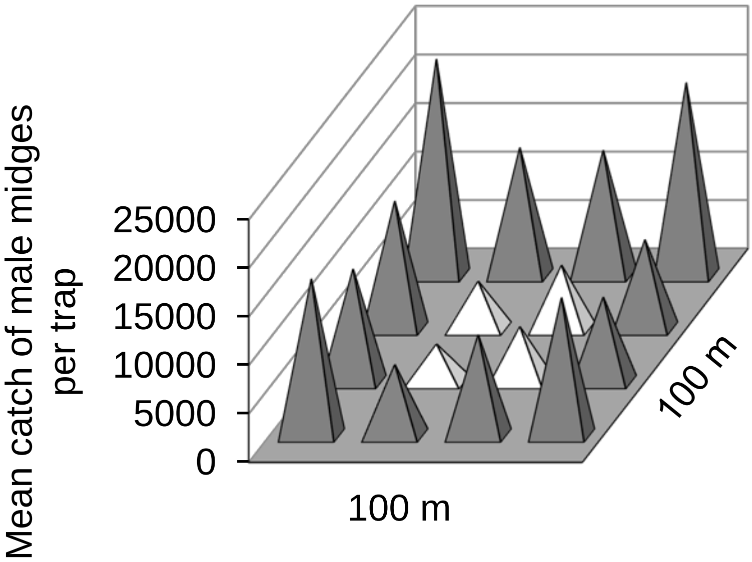

Mean catch of male midges per trap
25000
20000
15000
10000
5000
0
100 m
100 m

Fig. 5

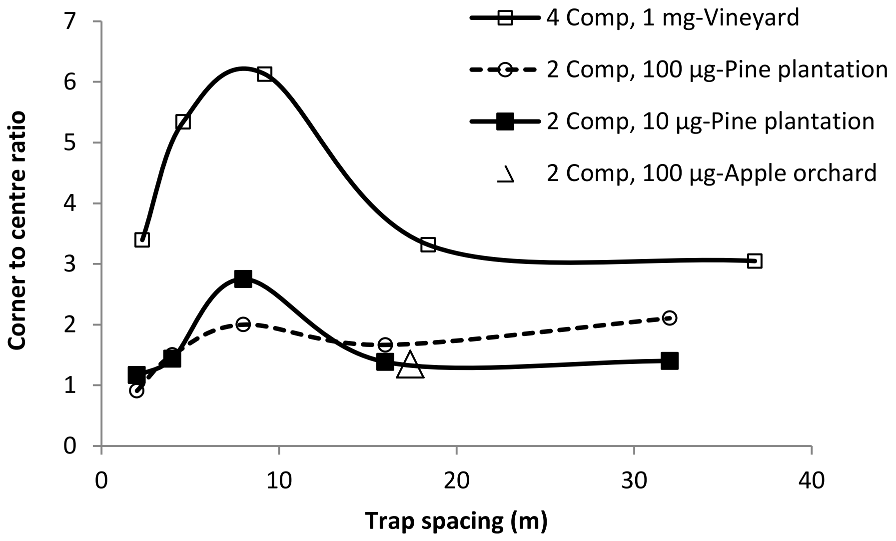

4 Comp, 1 mg-Vineyard
2 Comp, 100 µg-Pine plantation
2 Comp, 10 µg-Pine plantation
2 Comp, 100 µg-Apple orchard
Corner to centre ratio
0
1
2
3
4
5
6
7
0
10
20
30
40
Trap spacing (m)

Fig. 6

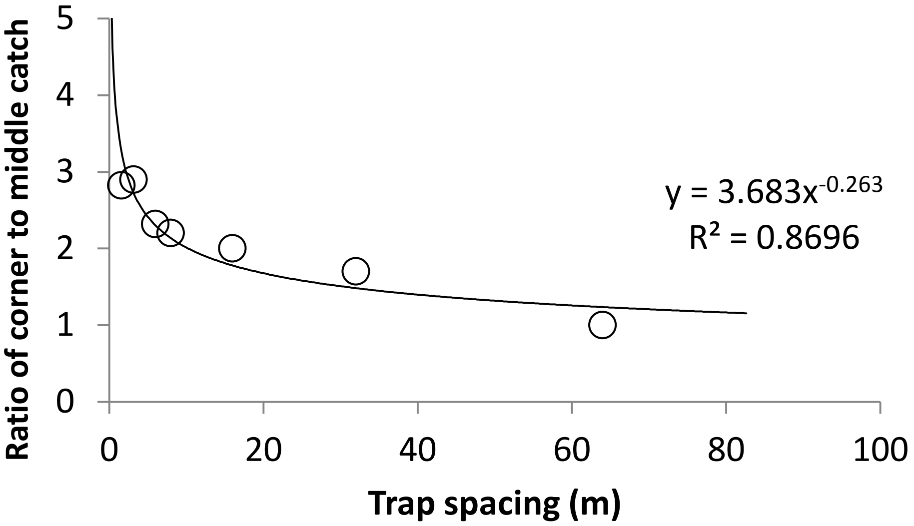
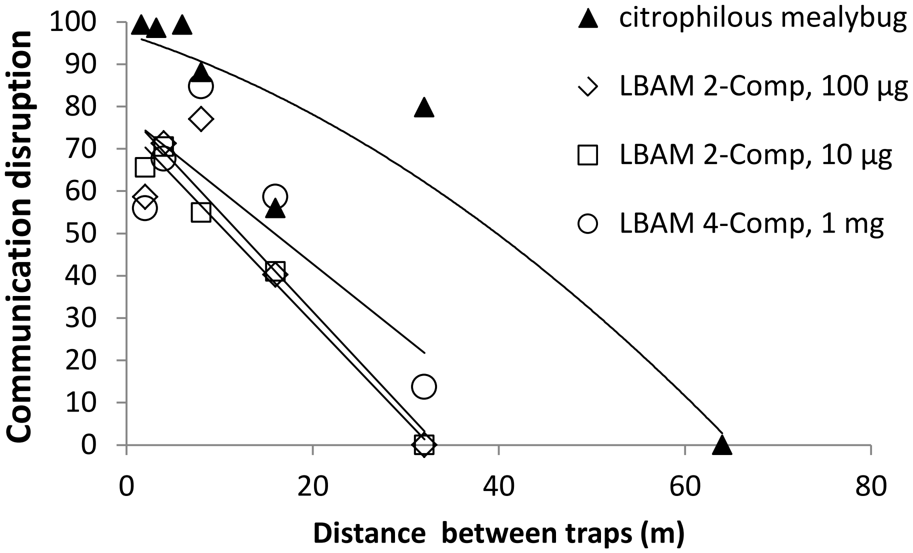

Ratio of corner to middle catch
5
4
3
2
1
0
0
20
40
60
80
100
Trap spacing (m)
y = 3.683x^-0.263
R² = 0.8696

Fig. 7



Communication disruption
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
Distance between traps (m)
▲ citrophilous mealybug
◇ LBAM 2-Comp, 100 µg
□ LBAM 2-Comp, 10 µg
○ LBAM 4-Comp, 1 mg

Fig. 8