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# Possible use of synthetic aggregation pheromones to control *Plautia stali* (Hemiptera: Pentatomidae) in kaki persimmon orchards[†]

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## ABSTRACT

1. The brown-winged green stinkbug *Plautia stali* Scott is the most serious pest of all noxious stinkbugs in various orchards in Japan. An area-wide integrated pest management program using the species-specific aggregation pheromone is desirable to control *P. stali* because non-specific insecticides may kill arthropod natural enemies and likely induce the resurgence of other endemic pests.
2. The traditional mass-trapping method is not expected to be effective due to huge migrations from cypress forests. Therefore, we chose an 'attract-and-kill' strategy of intensively installing poisonous eggplants with a synthetic aggregation pheromone lure as enclosures for the target orchards.
3. We could find no overall control effect of the installation of poisonous eggplants; however, the regional differences, which might come from topological configurations or the distance from source population in cypress forests, were conspicuous.
4. The poison eggplants with an aggregation-pheromone lure, however, change the spatial distribution of the fruit damage, appearing to induce the majority of the damage within a 100-m range of the poisonous eggplants. Some damage, although at a low level, was found in regions 100-200 m away from the poison eggplants.
5. We postulate that such low-damage regions were created because the majority of the bugs were swept away from the inside of the orchards to the areas of the poisonous eggplants. Our study, in which the spatial scale of the damage spillover was estimated at about 150 m, has important implications for future strategies of attract-and-kill or possibly push-pull.

***Keywords:*** *Attract-and-kill,* Plautia stali*, spatial autocorrelation structure, synthetic aggregation pheromone*

## INTRODUCTION

Since the early 1970s, a broad variety of orchards has been damaged every few years by abrupt swarms of stinkbugs. In fact, stinkbugs have become the primary pest of the Japanese fruit industry (Yamada, Tsutsumi, et al. 1991; Sato et al. 1997). The brown-winged green bug *Plautia stali* Scott is the most abundant and serious pest among these noxious stinkbugs, including *Halyomorpha halys* (Stål) and *Glaucias subpunctatus* (Walker), in most of Japan (Hasegawa & Umeya 1974). *P. stali* (hereafter referred to as 'bugs') is particularly cumbersome in the current framework of the integrated pest management (IPM) programs of Japanese orchards. This is in part because the bugs utilize orchards only temporarily during the non-reproductive season because of food shortages; their primary habitats and hosts are the cypress forests that generally surround the orchards (Moriya 1995). In fact, they can reach sexual maturity by feeding only on cypress trees including *Chamaecyparis obtusa* Sieb. & Zucc. and *Cryptomeria japonica* (L.f.) D. Don (Oda et al. 1981). Currently, the onset of swarms within the season can be predicted to some degree by observations of overwintering bug populations in the cypress forests (Yamada, Noda, et al. 1983) and by light trap monitoring in the orchards (Yamada, Tsutsumi, et al. 1991). However, it is still impossible to determine the exact time of the bugs' assault because it depends on the weather, temperature, and many other abiotic and biotic factors, including food densities (see also Tuda & Shima 2002). To keep the orchards free of stinkbugs, farmers must spray several times with organophosphate pesticides or synthesised pyrethroids, which has long after-effects. Such intensive applications of insecticides kill non-target arthropods, including the pests' natural enemies, and result in resurgence of the trivial endemic fruit pests (Kondo & Hiramatsu 1999; Morishita 2005). Killing the source population in nearby cypress forests will be an alternative option. However, aerial insecticidal application in cypress forests is impractical considering its enormous costs and immense area. Synthetic sex pheromones are currently playing an important role in area-wide IPM programs as a tool for pest monitoring and controlling (Pimentel 2007). The aggregation pheromone emitted by male bugs was found to attract conspecific males and females (Moriya & Shiga 1984), and its identified main component was methyl [E,E,Z]-2,4,6-decatrienoate (Sugie et al. 1996). The synthetic aggregation lure is already commercially available from Shin-Etsu Chemical Co, Japan (Adachi et al. 2007). Although several trials using this aggregation lure to control bugs have already been conducted, their efficacies are still under dispute. For example, the autodissemination of *Beauveria bassiana* E-9102 using the aggregation lure was tested in the field and caused an infection of as many as 30% of larval and adult bugs (Tsutsumi et al. 2003). However, it is still unclear whether the contagious power of this autodissemination device is sufficient to suppress the abrupt swarming of bugs into the orchards. On the other hand, traditional mass-trapping methods are not realizable considering the massive size of the background population living in the cypress forests. Moreover, continuous migrations from these forests would diminish the efficacy of mass trapping because the adult bugs can fly an average of 11 km per night (Moriya, Shiga & Maguchi 1987). In this study, we intensively installed poisonous eggplants baited with a synthetic aggregation pheromone as an attract-and-kill method; that is, the target areas (the kaki persimmon orchards to be protected) were enclosed by rows of dense poisonous eggplants with an aggregation-pheromone lure. Although there was a concern

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about the possible spillover of bugs from the aggregation lure, we assumed that this intensive installation of poison eggplants would be enough to divert bugs from the orchards and kill them at the eggplant barrier. Our first step was to test the overall efficacy of the strategic installation of these poisonous eggplants by comparing the number of damaged fruits between treated and control orchards. The spatial distribution of the fruit damage inside the orchards was described in detail to see whether this intensive installation could alter the bugs' distribution and consequently minimise damage to the fruits.

## METHODS

The time schedule of all of the events in Experiment 1, Experiment 2, and Experiment 3 (see below) is summarised in a schematic flowchart (Figure 1). Experiment 1 was conducted in the early autumn of 2003 and Experiment 2 and Experiment 3 were conducted in the early summer of 2004.

### Poisonous eggplants baited with a synthetic aggregation pheromone

For our study, we developed a new system of constructing the sex pheromone trap—as an attract-and-kill device. Instead of using the traditional pheromone traps with sticky sheets or water pans to catch insects, the aggregation lure was hung on a living plant treated with high-dose insecticides. This effectively kills bugs that suck out the plant tissues. A rootstock species of eggplant (*Solanum torvum* Sw) was planted in a multipurpose plant pot ($35 \times 65 \times 30$ cm). An insecticide for the bugs (Imidacloprid: ADMIRE®; Kumiai Chemical Industry Co. Ltd., Tokyo, Japan; equivalent to 1 g of active ingredient) was applied to the eggplants after they reached 1 m in height. The aggregation lure (34 mg of methyl [E,E,Z]-2,4,6-decatrienoate) was hung when the plant trap was installed in the experimental area (hereafter referred to as 'poisonous eggplant'). The system is quite effective, labour saving, and inexpensive compared to the standard pheromone traps. Our poisonous eggplants could kill 10 times more bugs than the 3-liter water basin trap that is generally used (Kogane-call®; Sankei Chemical Co., Japan; T. T., unpublished data). Moreover, watering to keep the plants alive is the only maintenance required for the system because its attract-and-kill effects continue for over a month.

### Experiment 1 (attract-and-kill trial)

The experiments were conducted in the cities of Ukiha and Asakura, Fukuoka Prefecture, from early September 2003. We selected six areas ranging from 46 to 114 ha where the main land use was for kaki persimmon orchards (Table 1). Poisonous eggplants with an aggregation-pheromone lure were installed in three of the areas (TR-1, TR-2, and TR-3). These treated areas were randomly chosen and enclosed by poisonous eggplants. The others areas were left free of the poisonous eggplants as control areas (CT-1, CT-2, and CT-3). All of the areas were located in the middle of the valley along the Chikugo River. Each was adjacent to the cypress forest (apart by only several hundred meters); TR-3, in particular, was located deep inside the cypress forests. Conventional insecticidal applications were performed within all areas according to decisions by the council of the kaki persimmon co-operatives in the two cities. These decisions were completely out of our control. Extensive spraying of the generic insecticides (Silafluofen: MR. JOKER WP®; Bayer CropScience, Tokyo, Japan) was conducted on 30 September 2003 in the middle of the experiment over all areas except CT-3 (Figure 1). Because the council recommends uniform insecticidal application within all orchards of the city in terms of procedure and dose, we assumed that the effect of the insecticide application could be minimized for the purposes of comparing the treated and control areas. Area CT-3 in Asakura City was treated according to a different spraying schedule; that is, the other generic insecticide (Dinotefuran: STARKLE®; Mitsui Chemical Inc., Tokyo) was sprayed during the experiment on both 22 September and 10 October 2003 (Figure 1). We will briefly discuss the plausible effect of this different spraying procedure between area CT-3 and the other areas.

The poisonous eggplants were installed to enclose the treated areas (TR-1, TR-2, and TR-3) on 5 and 6 September 2003 before the bug swarms arrived (Figure 1 & Figure 2). These poisonous eggplants were located regularly around the treated areas at a distance of 50 m each of other. However, there were several large gaps in the middle of this row of poisonous eggplants as a result of topological limitations and the unexpected demands of residents for removal of the traps. The maximum gap was 400 m in area TR-2 (Figure 2). A census of damaged fruits was conducted on 15 and 16 October 2003, 15 days after the first bug swarm (Figure 1). All 6 areas were subdivided into $40 \times 40$-m2 quadrats, resulting in 174, 312, and 205 quadrats in areas TR-1, TR-2, and TR-3, respectively, and 235, 150, and 179 quadrats in areas CT-1, CT-2, and CT-3, respectively. With the aid of handheld global positioning system (GPS) units (Otuka & Yamanaka 2003), 50 kaki persimmon fruits were randomly selected inside a quadrat of each area, and we recorded the number of damaged ones per 50 fruits as a representative of each quadrat. Whether the damage to the fruits was due to bugs was determined based on the typical feeding marks of bugs (Takagi & Mishiro 1996). The census was conducted by two kaki persimmon tree experts in each area. Because there were many unavailable quadrats, e.g. early harvesting of orchards and various land uses other than the kaki persimmon orchards, the area covered by our census ranged from 30.2% to 55.1% (Table 1). Consequently, we could not distribute the number of quadrats equally among the areas.

### Experiment 2 (detecting the range of damage induced by the poisonous eggplants)

The experiment to identify the relationship between the fruit damage and the distance from the rows of poisonous eggplants was conducted in Asakura City (33°2156E, 130°4530N). A straight row of the eggplants was established, with 32 poison eggplants at every 20-m distance on 1 July 2004 (Figure 1). Bug swarming was expected in early July, considering the preceding population census in the neighbouring cypress forests; however, a massive attack was observed at night when the poisonous eggplants were installed. The attack was so intensive that on day 2, the poisonous eggplants were almost defoliated by the bug sucking; in fact, more than 200,000 adult bugs were killed by the poisonous eggplants on that day alone (we roughly counted the number of corpses remaining in the pots of poisonous eggplants). The poisonous eggplants were retrieved on 4 July 2004. A few individuals were killed

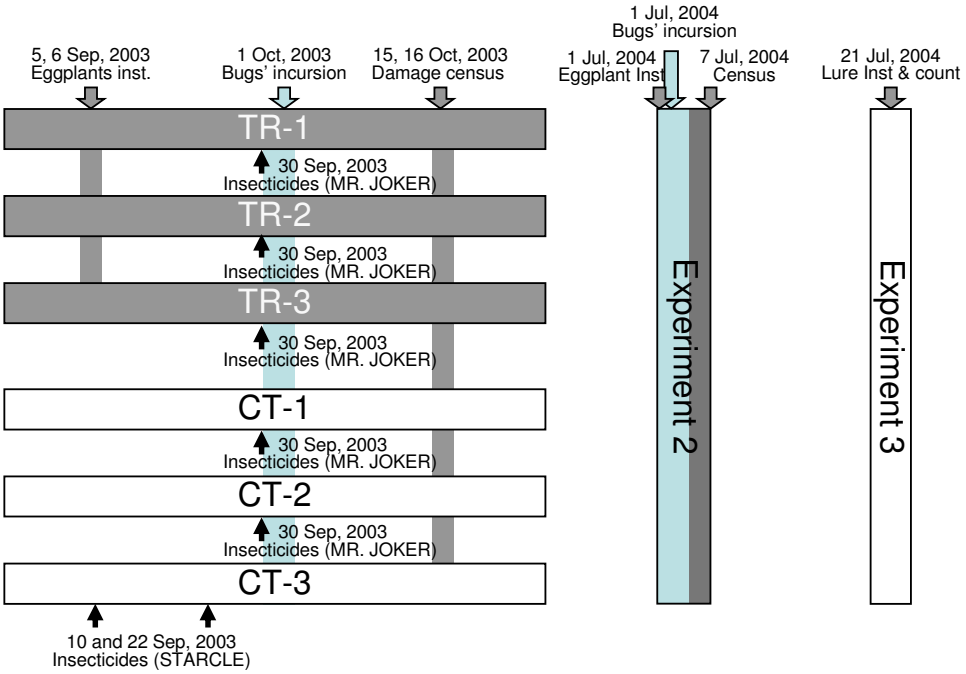


**Figure 1.** A schematic flowchart of the experimental timeline. The light grey arrows represent stinkbug incursion. The black arrows represent the timing of the insecticide applications.

**Table 1.** Description of experimental areas

| Experimental area | Location | No. of traps | Area | Portion censused |
|---|---|---|---|---|
| CT-1 (adjacent to CT-2) | Yoshii-chou Tominaga, Ukiha city (33°1954E, 130°4443N) | 0 | 62.5ha | 51.9(%) |
| CT-2 (adjacent to CT-1) | Yoshii-chou Takatori, Ukiha city (33°1944E, 130°442N) | 0 | 46.3ha | 42.1(%) |
| CT-3 | Yamada, Asakura city (33°2156E, 130°4530N) | 0 | 56.9ha | 41.9(%) |
| TR-1 | Uchiha-chou Miharu, Ukiha city (33°2034E, 130°4956N) | 65 | 62.5ha | 30.2(%) |
| TR-2 | Yoshii-chou Fukumasu, Ukiha city (33°1951E, 130°4548N) | 53 | 114.9ha | 40.6(%) |
| TR-3 | Yoshii-chou Tominaga, Ukiha city (33°2340E, 130°4353N) | 46 | 56.6ha | 55.1(%) |

after the initial defoliation, but many were simply attracted to the area around the lures in the poisonous eggplants. No insecticide application was used during the experiment. The number of fruits that fell on the ground because of the intensive sucking by bugs was counted at each of the 28 quadrats (10 × 10 m) in the kaki persimmon orchards on 7 July 2004. The quadrats were set up so that their numbers were about equal at each distance level (<100 m, 11; 100-200 m, 9; 200-300 m, 8). The distance from each quadrat to the row of poisonous eggplants was measured by a laser rangefinder (Nikon Laser 600®; Nikon Vision Co. Ltd., Japan). It should be noted that the quadrats were much smaller than those in Experiment 1 because higher resolution of the distance effect from the poison eggplants is required, plus we wanted to save the labour of counting all of the damaged fruits. Since fruits aggressively sucked by stinkbugs were automatically dropped and there were no fruit drops observed before the onset of the bug swarm, the number of fruits dropped could be assumed to be a direct representation of the intensive swarming of the bug attack.

**Experiment 3 (attractive range of an aggregation lure)**

In addition to Experiment 2, the attractive range of a single aggregation lure was measured by direct observation of the attracted individuals. A windbreak net (DioNet140®; Dio Chemicals Co. Ltd., Japan) 150 m long and 3 m high was attached to poles every 3-5 m along the roads around the Fukuoka Agricultural Research Center (33°2935E, 130°315N). An aggregation pheromone lure was hung at the 50-m point from the upwind end of the windbreak net (1.5 m height) at 17:00 on 21 July 2004, the time that the bug swarm was expected. It should be noted that we did not set up our experimental design in a circular fashion of trap coordinates, an approach that is normally used to test the attractiveness of pheromone traps (e.g., Turchin & Odendaal 1996; Schlyter 1992), because we needed to count the number of individuals perching around the trap rather than

those captured by the trap, and it was impossible to count the massive number of individuals perching in a short period other than our experimental design. Thirty quadrats (1 m in length and 3 m in height) were set up for every 5 m on the windbreak net. At 21:00, the number of bugs in each quadrat was counted. It was a clear and hot (28 °C) night and the wind was weak, less than 5 m/s from North-West as recorded by the nearest weather station (Asakura AMeDAS station, 33°2418E, 130°4142N, Japan Meteorological Agency).

## STATISTICAL ANALYSIS

All of the statistical analyses were conducted using the free statistical software R (Team 2025). The packages used in this study are all available from the CRAN.

### Generalized linear mixed-effect model (GLMM) for Experiment 1

We took a large number of quadrats inside the areas (150-312). It is traditionally well recognized that large replications within an area contribute to the precision of the area's summary statistics rather than to the statistical power to detect the treatment effect among areas (Hurlbert 1984). Although this approach admittedly has less statistical power than those with a large number of areas, our experimental design can still be modelled by the linear mixed-effect model, which is almost the same as a nested ANOVA but has fewer degrees of freedom and focuses more on the treatment effect (Faraway 2006). We employed the generalised linear mixed-effect model with Poisson error (GLMM) instead of the linear one (Gaussian error) because the number of damaged fruits per 50 fruits varied greatly and may follow the Poisson distribution. The *glmmML* package in R is available for this purpose. The predictor was categorical (i.e. treated or control) and was nested to each area. The $\chi^2$ approximation test was employed to test the fixed effects (the treatment effect) and the bootstrapping likelihood ratio test was used to test the random effect (the differences among areas). See the glmmML package manual and Faraway (2006) for details.

### Generalized additive models (GAMs) to see the effect of distance from the poisonous eggplants (Experiment 1)

GAMs were fitted to the data to see the relationship between the number of damaged fruits and the distance from the poisonous eggplants in all treated areas. GAMs were employed instead of the generalised linear model (GLM) because of the highly non-linear relationships that were expected between the number of damaged fruits and the distance from the nearest poisonous eggplants. The poisonous eggplants were installed to enclose the treated areas and were not regularly arranged. Assume that yi is the number of the damaged fruits of a tree in quadrat ($i$) and $d_i$ is the distance from the nearest poisonous eggplant. We can model the relationship as follows:

$$\begin{aligned} y_i &\sim \text{Poisson}(\mu_i) \\ \log(\mu_i) &= s(d_j) \end{aligned} \tag{1}$$

where Poission is the Poisson distribution with the mean $\mu_i$. $s(d_i)$ is the spline predictor of di smoothed by the thin plate regression spline (Wood 2006). Using the *mgcv* package in R, we constructed GAMs and then visually inspected the plotting of the spline predictor along $d_i$. The spline predictor reflects the number of damaged fruits in a logarithmic manner. For example, $s(d_j) = 0$ represents one damaged fruit of a tree in the quadrat and a negative value corresponds to <1.0 damaged fruit. The degree of freedom, which regulates the smoothness of $s$, was automatically estimated by the generalised cross-validation algorithm (Wood 2006).

### Spline correlograms for Experiment 1

Correlogram analysis is one of the standard techniques used to detect the range of spatial similarity, which is possibly caused by the dispersal processes between habitats (e.g., Sokal & Oden 1978; Heino et al. 1997). Suppose the number of damaged fruits was counted for n points with $(x_i, y_i)$ coordinates $(i = 1, 2, \cdots, n)$ in each area. Then the sample autocorrelations between point-$i$ and point-$j$ $(i \neq j)$ are calculated as a product-moment standardised by the variance as

$$\hat{\rho}_{ij} = \hat{\rho}_{ij}(z_i, z_j) = \frac{(z_i - \bar{z})(z_j - \bar{z})}{\frac{1}{n}\sum_{l=1}^{n}(z_l - \bar{z})^2}. \tag{2}$$

To see how the autocorrelation varies along the distance between point pairs, Moran's I has been traditionally used (Cressie 1993). It calculates the average $\hat{\rho}_{ij}$ values in a distance category and plots them along the average distances in this category. The spatial dependencies are visually postulated by straight line connections. Recent advances in computer power enable us to calculate more flexible spline correlograms than the somewhat awkward stepwise function in Moran's I (e.g., Bjørnstad & Falck 2001; Yamanaka et al. 2007). Using a cubic B-spline as an equivalent kernel smoother, the nonparametric correlogram function (NCF) can be directly fitted to all $\hat{\rho}_{ij}$ for $n(n-1)/2$ pairwise combinations among $n$ spatial points. There are two major advantages to NCF over Moran's I. First, it allows us to estimate the underlying spatial correlation function without assuming any functional form, such as spherical or Gaussian types of functions that are often used in geostatistics. Second, a bootstrapping algorithm can generate the confidential envelope along the NCF (Bjørnstad & Falck 2001). Consequently, the zero-intersection of the spatial correlogram can be estimated with confidential limits which can be interpreted as the range of spatial similarity (Sokal & Oden 1978). The number of damaged fruits was log-transformed after adding 1.0. The spline correlogram for the transformed damage was drawn for each area with the *ncf* package in R. The 95% confidence limits of the spatial correlation were estimated by bootstrap with 1,000 data re-samples.

### Kriging maps (Experiment 1)

We drew kriging maps to visually see the spatial trends. The (semi-)variogram analysis in which kriging is conducted is a method akin to the correlogram of the previous analysis. It has a large variety of mapping tools and is specifically utilised in geostatistics rather than in biology or ecology. We chose it only because there is no R-package available to make spatial predictions using NCF. The variogram analysis uses data variance instead of correlation in the correlogram analysis. When variogram values are plotted along the distance, the values are small for short distances of the point pairs, increase

with increasing distance, and then usually level off or become constant after some distance. We call this levelling-off *sill* and can interpret it as the overall (non-spatial) variance of the data. The distance at this levelling-off is known as the *range* and somehow indicates the scale of the spatial dependencies in the data. The intercept at the ordinate is the *nugget*, the unmeasured variance including with the experimental error. For details, see Cressie (1993) and Liebhold et al. (1993). The number of damaged fruits was log-transformed after adding 1.0 and three parametric models, i.e. Gaussian, spherical, and exponential, were fitted to the data variogram for each area using the *geoR* package in R. The mathematical formulae of the parametric models can be found in Bivand et al. (2008). We chose the best model based on Akaike Information Criterion. The basic statistics (sill, range, and nugget) were then estimated and the kriging maps were drawn using the best parametric model. Although we report these statistics, we only tried to visually interpret the kriging map.

**Use of GLMs for Experiments 2 and 3**

GLM were fitted to the data to see the effective range of the poisonous eggplants and the aggregation lure. GLMs were employed instead of GAMs because the linear relationships could be assumed here in log scale. GLMs are formulated in a manner similar to equation 1 but have no spline function term:

$$\begin{aligned} y_i &\sim \text{Poisson}(\mu_i) \\ \log(\mu_i) &= d_0 + d_j \end{aligned} \tag{3}$$

In Experiment 2, $y_i$ is the number of the fruits dropped in the quadrat ($i$) and $d_i$ is the distance from the rows of poison eggplants while yi is the number of bugs settling on the quadrat ($i$) and $d_i$ is the distance from the aggregation lure in Experiment 3. $d_0$ is a $y$-intersect of the predictor. We first checked the effect of the distance, and then the $x$-intercept (corresponding to 0 fruit dropped in Experiment 1 and 0 bugs in Experiment 2) and its 95% confidence interval were calculated by bootstrap with 1,000 data re-samples.

## RESULTS

**Experiment 1 (attract-and-kill trial)**

The GLMM showed that the difference in effect of the poisonous eggplant treatment was not statistically significant ($\chi^2$ approximation test; $z = 0.985$, $df = 1$, $P = 0.324$), but the nested effect was prominent ($P < 0.0001$ by likelihood ratio test of 1,000 times bootstrapping). These results indicate that the poisonous eggplants had no effect in suppressing the damage, although the regional damage differences among the areas were conspicuous. This may be partly because the poison eggplants could not perfectly enclose the treated areas (Figure 2) or because the poisonous eggplants did not originally have enough barrier power to prevent the bugs from penetrating.

The spatial configurations of the damaged fruits are shown in Figure 2 (treated areas) and Figure 3 (controls). Although no suppression effect was observed, there were slight differences between the spatial configurations of the damage in the treated and control areas. The kriging maps were drawn behind the census points to see the smoothed spatial trends (Figure 2 & Figure 3, left panels). The estimated parametric models were TR-1 (Gaussian, *range* = 98.2, *sill* = 0.72, *nugget* = 0.42), TR-2 (Exponential, *range* = 188.3, *sill* = 0.81, *nugget* = 0.57), TR-3 (Spherical, *range* = 112.8, *sill* = 0.83, *nugget* = 0.26), CT-1 (Gaussian, *range* = 199.5, *sill* = 0.48, *nugget* = 0.37), CT-2 (Gaussian, *range* = 199.8, *sill* = 0.93, *nugget* = 0.80), and CT-3 (Gaussian, *range* = 98.2, *sill* = 0.54, *nugget* = 0.11). Although we will see the NCF results later, the results were basically concordant with those of the NCF. The parametric models for the variograms had smaller spatial dependencies in the treated areas. The nuggets were substantially high compared to the sills in all areas. These results suggest that the variations in numbers of damaged fruits were very large and that there were only small spatial structures in these areas. Visual inspection (Figure 2 & Figure 3) revealed that the heavy damage in the treated area was observed as clustered (eg, TR-1, centre bottom area of Figure 2a; TR-2, centre bottom area of Figure 2b), while the damage was scattered in the control areas (Figure 3). We suspect that the escape of bugs from the attractive range of the poisonous eggplants was the reason for these clustering patterns of the damaged fruits. However, these tendencies were obscure and it is difficult to draw a clear conclusion because the quadrats (i.e. kaki persimmon orchards), especially in areas TR-1 and TR-2, were fragmented and covered a small portion of the whole area. Contrary, the pattern of damage in area TR-3 seemed different from that of areas TR-1 and TR-2. The damage in area TR-3 was concentrated in the northwest part. TR-3 was entirely situated on a hill, and the spatial pattern of the damage was directly influenced by this topography. The migrants from the cypress forest located in the northwest could fly over the rows of the poisonous eggplants that were placed at the bottom surrounding the hill and land inside the experimental area. Correlogram analyses using NCF provided basically the same results as visual inspection of the kriging map (Figure 2d,e&f, Figure 3d,e&f). The estimated intersections with the $y$-axis were large (0.493, 0.495, and 0.423 in areas TR-1, TR-2, and TR-3, respectively) (Figure 2d,e&f), while those in the control areas were small (0.252 and 0.116 in areas CT-1 and CT-2, respectively). Therefore, the treated areas had strong clusterings of fruit damage within short distances since the y-intersection represents the strength of the spatial autocorrelation in a very short distance (Bjørnstad & Falck 2001). The estimated $y$-intersection in area CT-3 was, however, as large as 0.532 and was comparable to that in the treated areas. Although we do not have any clear explanation for it, the different spraying schedule in CT-3 might be the reason. In all cases except CT-3, the first bug swarms occurred 1 day after the first spraying, at which time the pesticide concentration was still uniform. However, the first bug swarms occurred 8 days after the first spraying in area CT-3. By this time, the pesticide concentration might have changed to a heterogeneous distribution and, therefore, different spatial configurations of bugs (Figure 3c). The spatial scale of the autocorrelation was more compact in the treated areas (204.5, 169.1, and 136.2 m in areas TR-1, TR-2, and TR-3, respectively), whereas those of areas CT-1 and CT-3 were much larger (288.4 and 274.5 m, respectively). This result also supports the conclusion that presence of the poisonous eggplants helped concentrate the distribution of the fruit damage. The spatial autocorrelation was 168.3 m in area CT-2, nearly equal to those of the treated areas. This

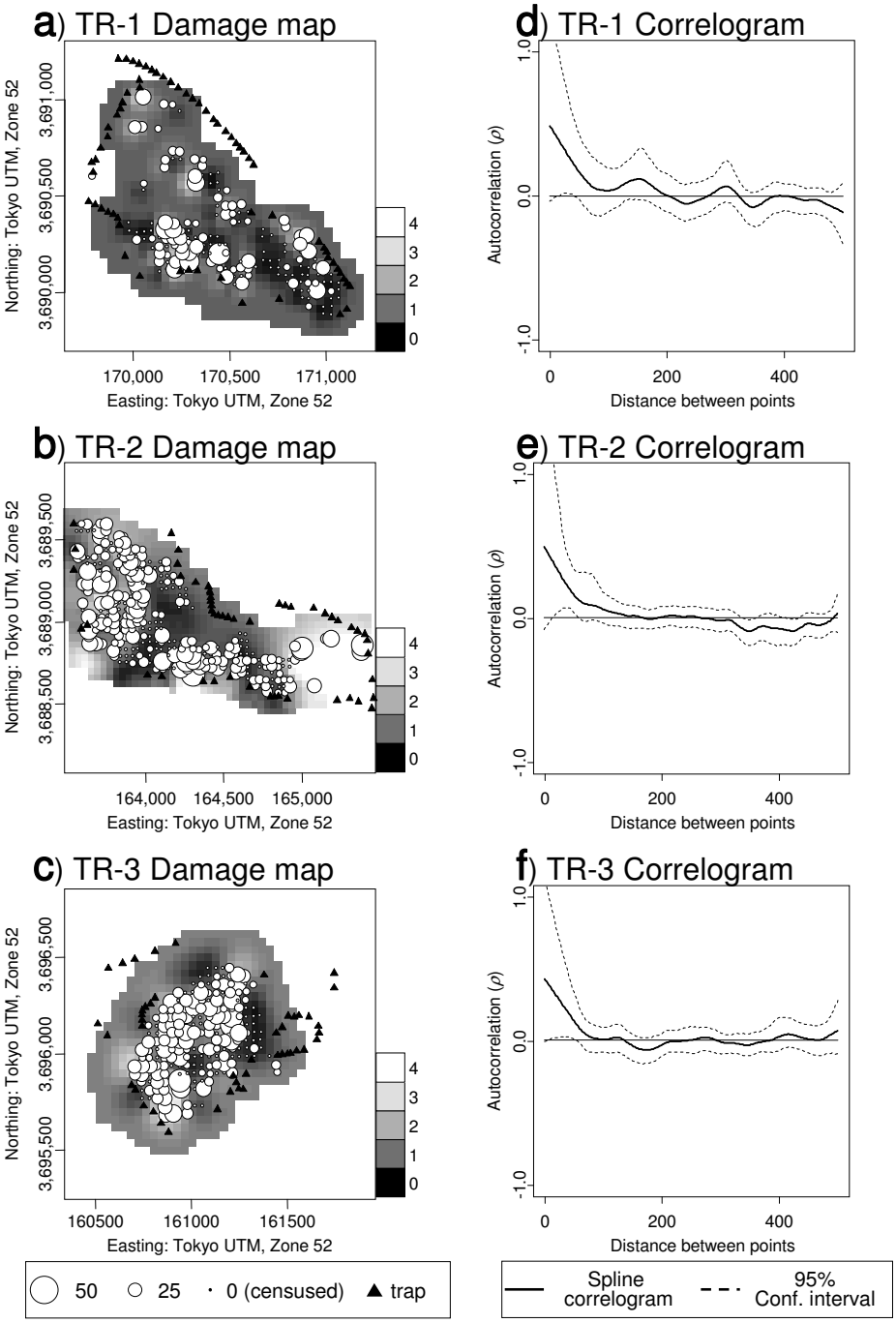


**Figure 2.** Spatial trends of the fruit damage (**a**-**c**) and their spatial autocorrelation structure (**d**-**f**) in the treated areas (TR-1, TR-2 and TR-3, respectively). The censored points in the quadrats were plotted as hollow circles according to degree of damage, and the positions of the poison eggplants were also plotted as solid black triangles (**a**-**c**). Density images of the damage behind the censored points were generated by kriging after the (**a**) Gaussian, (**b**) exponential or (**c**) spherical model fitting. Nonparametric (spline) correlograms (solid lines in **d**-**f**) were calculated to show the spatial structure of the damage. For details, see text.

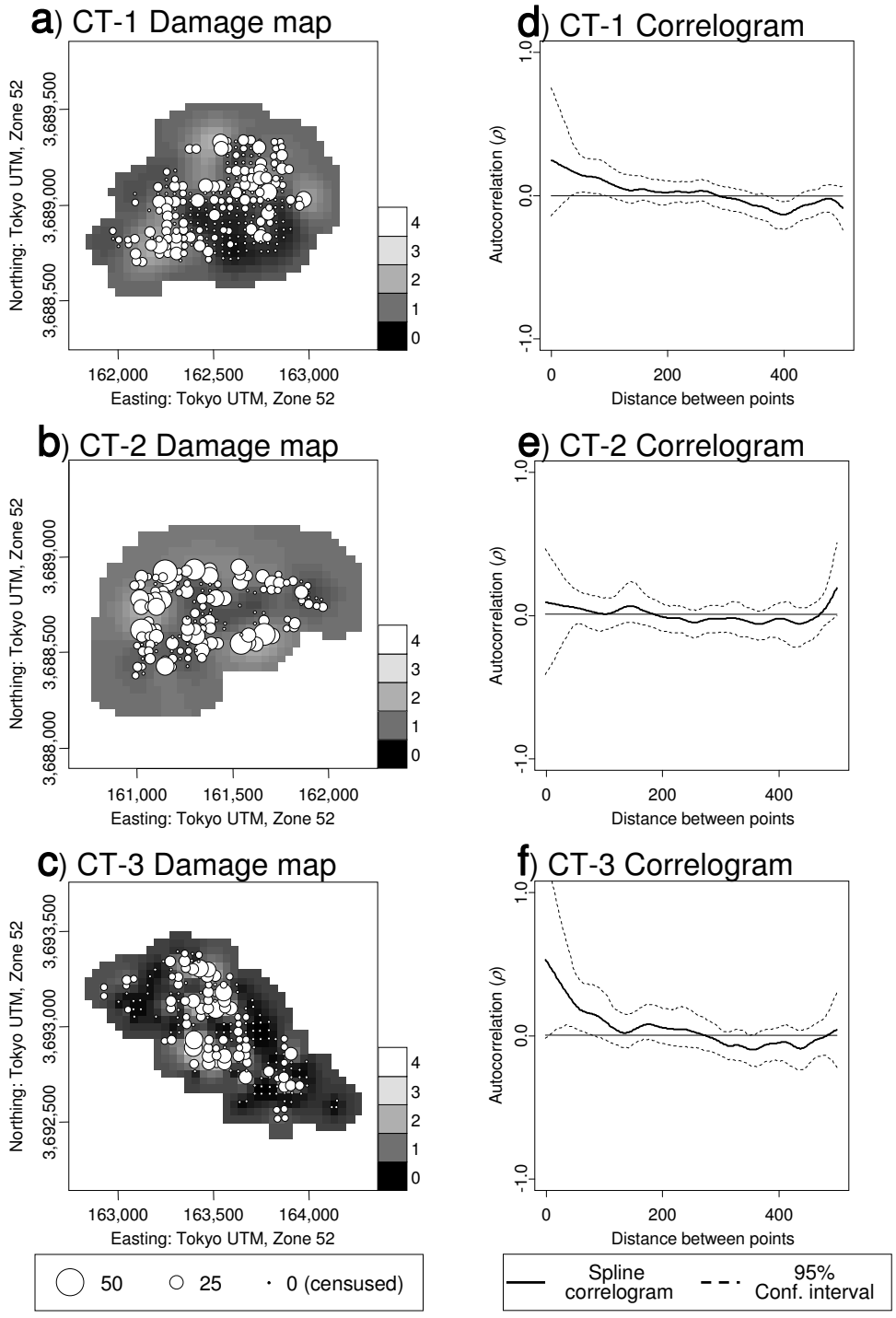


**Figure 3.** Spatial trends of fruit damage (**a**-**c**) and their spatial autocorrelation structure (**d**-**f**) in the control areas (CT-1, CT-2 and CT-3, respectively). Density images of the damage behind the censored points were generated by kriging after the Gaussian (**a**-**b**) or exponential (**c**) model fitting. Denotations are similar to those in Figure 2.

may be because CT-2 was a rather small experimental area and, consequently, the damage within it was compact.

Using GAMs, we tried to model the relationship between fruit damage and distance from the nearest poisonous eggplant. The relationship was highly non-linear in all the three treated areas (Wald tests, $P < 0.001$) (Hastie & Tibshrani 1990). The GAM for TR-1 shows that the spline predictor was estimated to be 0 at about 70 m from the nearest poisonous eggplant (Figure 4a) and then increased a little again around 120 m; however, the low level of damage continued until around 220 m. In TR-2 (Figure 4b), the spline predictor dropped to 0 at about 100 m and the low damage level continued until 150 m. However, the damage level in TR-3 expressed by the spline predictor was very low in the vicinity of the poison eggplant but gradually increased as the distance increased. These results were concordant with the visual inspection of the damage; i.e., intensive damage around the poisonous eggplants was observed in areas TR-1 and TR2, which might have been caused by the escape of bugs from the attraction range of the poisonous eggplants, while area TR-3 was affected more largely by the topographic configuration than by the poisonous eggplants.

**Experiment 2 (detecting the range of induced damage by the poisonous eggplants)**

No fruit drop was observed before the installation of the poison eggplants (1 July 2004). Because a massive attack was observed in the night when the poison eggplants were placed, a large number of fruit drops were observed on the survey date (7 July 2004). All of the fruits in the quadrat nearest the eggplants (228 in total) had been dropped because of the concentrated sucking by bugs. This massive drop was not incorporated into the GLM below because we found that a particular kaki persimmon tree that was adjacent to the poisonous eggplants played a role in the target by the bugs' attraction to the aggregation pheromone.

The number of fruit drops and the prediction by GLM are shown in Figure 5. The effect of the distance from the row of the poison eggplants was statistically significant ($\chi^2$ test; $z$ = 166.65, $df = 1$, $P < 0.0001$). The $x$-intercept was estimated as being 152.5 m (123.8-200.8 m; 95% bootstrapping confidence interval). Therefore, the spillover of bugs from the row of poisonous eggplants was estimated to have an effect in the range of 150 m over the 7-day period.

**Experiment 3 (attractive range of an aggregation lure)**

We counted 35,706 individuals settling on the windbreak net in the entire 30 quadrats. As anticipated, the number of bugs was larger downwind from the aggregation pheromone lure than upwind (Figure 6).

Because the attractive effect of the aggregation lure was obviously different downwind and upwind, we constructed separate GLMs for these directions. The effect of distance from the trap line was statistically significant both downwind and upwind ($\chi^2$ test; $z$ = -152.8, $df = 1$, $P < 0.0001$ to downwind, $z$ = 39.54, $df = 1$, $P < 0.0001$ to upwind). The x-intercepts were estimated to be 26.1 and 82.8 m (20.8-41.0 m and 73.2-89.1 m; 95% bootstrapping confidence interval) downwind and upwind, respectively. From this result, a single aggregation lure can create clustering over 80 m downwind in a single night.

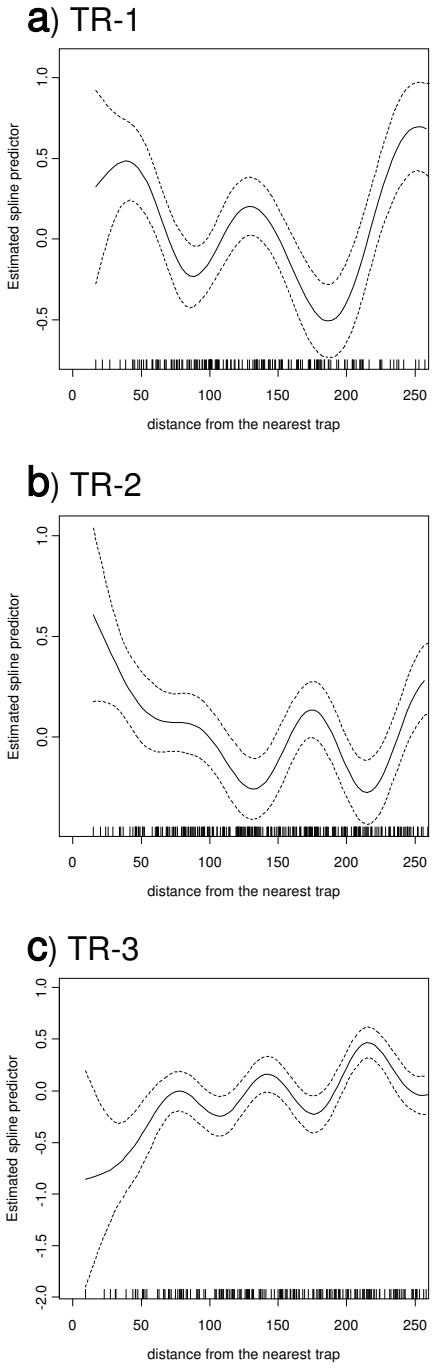


**Figure 4.** Relationships between the number of damaged fruits and the distance from the nearest poisonous eggplant. (**a** – **c**) correspond to treated areas, TR-1, TR-2 and TR-3, respectively. Estimated spline predictors, which represent log-scaled damage, were plotted along the distance from the traps. The dotted lines represent the lower and upper twice pointwise SE. Data points were also plotted as small ticks on the $x$-axis. For details, see text.

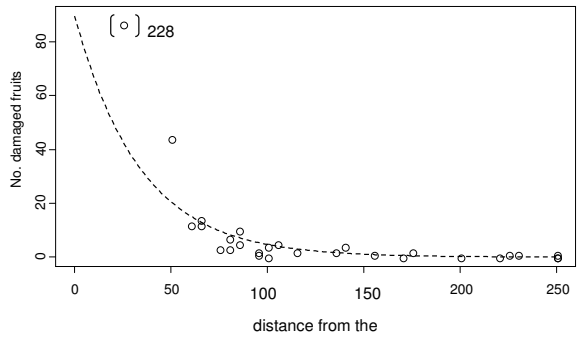


**Figure 5.** Effects of the distance from the trap lines on the number of fruit drops. A log regression (Poisson error) was executed after removal of the extremely large number of fruits (228) that dropped at 25 m. The open circles represent the data, and the dashed line represents the model prediction.

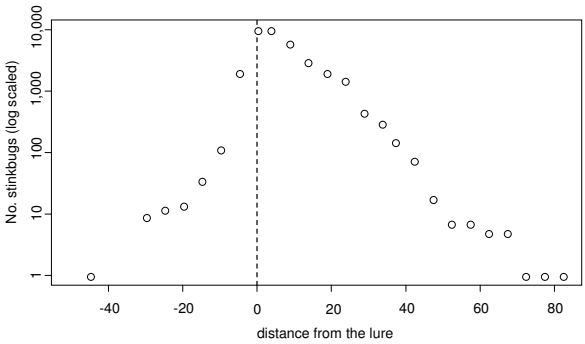


**Figure 6.** Range of the attraction effect of an aggregation lure. The number of fruit stinkbugs settling on the quadrats ($1 \times 3$ m in height) was counted for every 5 m downwind and upwind.

# DISCUSSION

We failed to find any beneficial effect of the attract-and-kill method of intensive installation of poisonous eggplants in Experiment 1. On the other hand, the regional differences among the areas were conspicuous. Such regional differences can be interpreted as due to the topological conditions of the orchards. Isolated kaki persimmon orchards in open paddies and crop fields and those close to cypress forests have been reported to be susceptible to the intensive bug attacks (Hastie & Tibshrani 1990). In our study, area TR-3, which is situated on a hill, had the second largest number of damaged fruits among the 6 areas. We postulated that the main reason is its location; that is, it is close to the cypress forests. In addition, we suspect that the insecticidal application also had a substantial effect on the reduction of fruit damage because the damage in area CT-3, in which the spraying of the insecticide was conducted twice, was the second smallest of all of the experimental areas. Although the controlling effect of the poisonous eggplants was dubious, we found that it changed the spatial distribution of the fruit damage. However, the presence of the poisonous eggplants seemed to induce rather than prevent fruit damage in the orchards immediately near them (Figure 4). The attraction range of the aggregation pheromone has been reported to be outspread rather than as a single point in this species (Moriya, Mabuchi, et al. 1993). We confirmed this in Experiment 3; that is, the attraction range was estimated to be more than 80 m downwind in a single night (Figure 6). Moreover, the range of damaged fruits expanded to approximately 150 m upon use of plural traps for several nights, as shown in Experiment 2 (Figure 5). Therefore, we conclude that the clustering of the bugs around the traps will be sustained because a great number of bugs gathered around or near the traps. Although many of them were killed by our trapping system, there was a continuous supply of them from areas well beyond the orchards. Bugs can fly as far as 11 km per night on an average (Moriya, Shiga & Maguchi 1987). Such spillover damage caused by the aggregation lures have already been reported in some forest pests, and it is recommended that pheromone traps be installed far from the target area (Ross & Daterman 1994). Our poisonous eggplants should have been installed far from the orchards. Although the negative effect of traps causing bug-induced damage was conspicuous, a slight protective effect inside the treated areas was found in areas TR-1 and TR-2. Low-damage regions were found 100-200 m away from the traps beyond the range of intense damage (Figure 4a&b). We elucidated that such low-damage regions were created not only because these ranges exceeded those of the spillover effect from the aggregation lures but also because the adults were swept away from these regions to the traps. Although we must conclude that our strategic installation of the aggregation traps did not reduce fruit damage, the discovery of the spatial scale (ca 100 m) of bugs aggregating around the traps has profound implications for the construction of strategies for future area-wide IPMs. A number of possible strategic arrangements other than that used in our current study are available. For example, a large number of the poisonous eggplants could be installed in less important woodlots around the orchards in which intensive application of insecticides would be possible. Using geographical information systems, we can choose woodlots

with suitable topography. The distance from the orchards should be greater than 100 m. In addition, a push-pull strategy can be considered. In recent decades, a push-pull strategy has been developed as a low-cost and basically nontoxic IPM methodology (Miller & Cowles 1990). This strategy uses attractants and repellents simultaneously to modify the insect pest behaviour. The most successful application of a push-pull strategy is the combination of intercropping with non-host repellent plants with attractive trap crops surrounding the target area (Khan, Pickett, et al. 2000; Khan, Midega, et al. 2008). While such a push-pull strategy is very effective, especially for small-scale farmers in countries with fewer resources, its idea is also applicable for pests like *P. stali* for which intensive pesticide application should be avoided (Cook et al. 2007). The poisonous eggplants in our study can be used to pull the pests from the target area, as long as they are not placed close to the orchard (>100 m away). Candidates for repellents include the use of yellow lights to prevent stinkbugs from orchards. This method has already been put into practice (Uchida et al. 1978). Various alert pheromones can be used as repellents in some stinkbug species (Yamashita & Isayama 2005), and a repellent for *P. stali* will possibly be found in the future. By creating a push-pull strategy, we can reduce the amount and number of insecticide applications, thereby reducing the first impact of sudden bug assaults. Our study, in which the spatial scale of the damage spillover was estimated to be approximately 150 m, has important implications for future attract-and-kill or possibly push-pull strategies.

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## Data Accessibility

The data supporting this study are not publicly available.

## Competing Interests

The author declares no conflict of interest.

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