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Evaluation of attract-and-kill strategy for management of cocoa pod borer, Conopomorpha cramerella, in Malaysia cocoa plantation

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ABSTRACT

In South-East Asia, cocoa production is dramatically affected by cocoa pod borer (CPB) infestations. As an alternative tool to chemical control, the efficacy of attract-and-kill strategy (CPB sex-pheromone as attractant and Delta trap without sticky liner sprayed with cypermethrin solution as killing station) was evaluated and compared with current standard CPB management approach as control treatment during two main cocoa harvest seasons in Malaysia (with 100 µg and 33.3 µg CPB-pheromone loading per station, respectively). In both seasons, attract-and-kill strategy was highly effective at reducing male flight activity ($p < 0.05$) in attract-and-kill plots comparing with standard CPB management plots. For the percentage of CPB-infested pods, the attract-and-kill strategy (100 µg) was as good as the conventional pesticide spray applications of cypermethrin ($p = 0.083$) in first season. However, it was significantly ($p = 0.021$) reduced in the second season with lower pheromone loading (33.3 µg), indicating that this semiochemical based strategy is far superior to and more feasible than the currently applied conventional synthetic pesticide treatment and is therefore a good alternative in CPB integrated pest management.

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1. Introduction

Insect infestation by the cocoa pod borer (CPB) moth, *Conopomorpha cramerella* (Snellen) (Lepidoptera: Gracillariidae), is the most important pest problem of cocoa (*Theobroma cacao* L.) cultivation in South-East Asia. Crop losses of 30% have been reported (Teh et al. 2006; Zhang et al. 2008) and in some cases even more extreme losses of 50% (Wielgoss et al. 2012) and 80% (Day 1989) were found. In Sulawesi, Malaysia, CPB-infestation adversely affects up to 80% of cocoa farms (Neilson 2007). In the 1990s, *C. cramerella* nearly caused a collapse of the cocoa industry in Malaysia and continued to be a serious problem in the country's cocoa sector (Shapiro et al. 2008). Until now, the management of *C. cramerella* has heavily relied on pesticide applications (Wood et al. 1992; Beevor et al. 1993), which is neither environmentally sustainable nor economically effective.

There has been a great deal of effort directed towards the development of integrated pest management (IPM) strategies that can be used against CPB in commercial cocoa cultivation. In an experiment in South Sulawesi, Indonesia, the use of degradable plastic pod sleeves for exclusion of CPB-moths reduced the number of CPB-infested cocoa pods from 62.26% in untreated control pods to 8.44% (Rosmana et al. 2010). The same researchers also tested the effect of spraying the entomophagous nematode *Steinernema carpocapsae* on the cocoa pod surface and found a reduction in number of CPB-infested pods to 4.88% as compared the same untreated control pods. In a lab bioassay, it has been showed that several Cry1-class proteins from *Bacillus thuringiensis* killed CPB-larvae (Santoso et al. 2004). However, the latter method has not yet been field-tested.

Behavioral manipulation of insects using semiochemicals is an ecological IPM-tactic that has received increasing attention for pest control. The sex pheromone components of *C. cramerella* were identified in 1986 (Beevor et al. 1986a, 1986b; Ho et al. 1987) and field-tested in Sabah, Malaysia. They consist of 40: 60: 4: 6 ratios of (*E,Z,Z*)-4,6,10-hexadecatrienyl acetate [(*E,Z,Z*)-16:OAc], (*E,E,Z*)-4,6,10-hexadecatrienyl acetate [(*E,E,Z*)-16:OAc], (*E,Z,Z*)-4,6,10-hexadecatrienyl alcohol [(*E,Z,Z*)-16:OH], and (*E,E,Z*)-

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4,6,10-hexadecatrienyl alcohol [(*E,E,Z*)-16:OH] (Beevor et al. 1986a). The CPB-sex pheromones attract male CPB-moths and can be used as a lure for monitoring of pest population or for actual pest control through mass trapping, mating disruption, or attract-and-kill strategies (see further) (Beevor et al. 1986b, 1993). Nevertheless, the use of pheromones against *C. cramerella* was halted in the early 1990s, partly due to the lack of commercial quantities of pheromone preparations available for large-scale use in above-mentioned CPB-control strategies (Zhang et al. 2008).

Recent research (Vanhove et al. 2015) revealed that pheromone blends with up to 47% of impurities [consisting of geometric isomers of the aforementioned 4 components, including (*E,Z,E*)- (*Z,Z,Z*)-, (*Z,E,Z*)- and (*Z,E,E*)-4,6,10-hexadecatrienyl acetates] have the same activities of capturing CPB-males than that of blends with only 5% impurities. Since above impurities in pheromone blend do not significantly affect effectiveness, mass production of CPB-pheromones using a more cost-effective synthetic pathway and subsequent use in CPB-control offer new, affordable prospects worth investigating.

In pest control by behavioral manipulation, sex pheromones can be effective in different ways. In mass trapping, the aim is to reduce the pest population below economically damaging levels by the application of a high number of pheromone-baited traps (El-Sayed et al. 2006). Mating disruption relies on confusing male insects by sex pheromones so that they are no longer able to locate the females, thus reducing fecundity and eventually population size (Sanders 1997). In cocoa, a mass trapping trial using sex pheromones was shown to reduce *C. cramerella* infestation from averagely 475 to 150 damaged pods per ha per week after 120 days in large-scale pilot studies (>200 ha) (Beevor et al. 1993). Whereas a mating disruption trial revealed that it could reduce mating ratios of females from 99% to 80% in control and treatment plots, respectively (Alias et al. 2004).

Attract-and-kill is another and hitherto unexplored pheromone-based IPM-technology that might be used against CPB in cocoa cultivation. In this method, the insect pests are also attracted by pheromone lures, but unlike in mass trapping, where the insects are entrapped, they are subjected to a killing agent (usually an insecticide) applied at the source of the attractant, which eliminates target individuals from the population shortly upon exposure (El-Sayed et al. 2009). Attract-and-kill technology has been effectively used to control many insect pest populations (Witzgall et al. 2010). Recent examples include successful pheromone-based field experiments against codling moth (*Cydia pomonella*) in apple (*Malus domestica*) orchards (Charmillot et al. 2000; Mansour 2010), against *Carpophilus* spp. (Coleoptera) in Australian stone fruit orchards (Hossain et al. 2008), and against citrus leafminer (*Phyllocnistis citrella*) in US orange (*Citrus x sinensis*) orchards (Stelinski and Czokajlo 2010).

Observed correlations between pheromone-based CPB catch data and the number of cocoa pods with *C. cramerella* infestation symptoms reflect the dependences of the CPB-moth's feeding activity on ripe cocoa pods (Vanhove et al. 2015). Furthermore, the overwhelming numbers of male *C. cramerella* captured in traps baited with pheromones in earlier experiments (Tay and Sim 1989; Beevor et al. 1993; Alias et al. 2004; Zhang et al. 2008) suggested that a strategy of attract-and-kill could ultimately result in reductions of populations below damaging levels. It may provide an alternative, less hazardous solution to the common cocoa pest control strategy of conventional insecticides that are directly applied on the trees. Attract-and-kill technology uses much less pheromone than mating disruption and mass trapping because a lower density of killing stations is required (El-Sayed et al. 2009). In combination with CPB-pheromone production that uses a more cost-effective synthetic pathway (Vanhove et al. 2015), attract-and-kill strategy has great potential to be used as an appropriate and affordable approach in CPB management.

In this paper, we report the results of two successive attract-and-kill seasons, in which lures with different CPB-pheromone loadings were used on a Malaysian cocoa estate.

2. Material and methods

2.1. Experimental plantation

Research was performed on a 61-ha cocoa plantation in Padang Tengku, Pahang Province of peninsular Malaysia, where 7 cocoa clones (PBC130, PBC131, PBC139, PBC123, PBC140, PBC159 and PBC113) were planted in 1989 in North-South-oriented rows (repeated sets of 4 rows of each clone) in a monocrop cocoa system with trees spaced at 3 m × 3 m (1,111 trees per ha). The north and west of cocoa plantation is bordered by a 1,100-ha rubber plantation, which is part of the same estate as the cocoa fields. To the south are cocoa seedling nurseries and estate offices and to the east is a village inhabited by estate workers. No other cocoa plantations exist in the wide area where agriculture mostly consists of small-scale fruit and vegetable growers and large oil palm estates.

2.2. Lure formulation

The CPB-pheromones were produced by the Invasive Insect Behavior and Biological Control

Laboratory (IIBBL, Beltsville, MD, USA) using an alternative to the synthetic pathway reported by (Beevor et al. 1986a), resulting in a pheromone blend 5 containing (*E,Z,Z*)-16:OAc: (*E,E,Z*)-16:OAc: (*E,Z,Z*)-16:OH: (*E,E,Z*)-16:OH in a ratio of 40:60:4:6 with up to 45% of other geometric isomers (Vanhove et al. 2015). However, it was shown that the degree of other isomers did not significantly affect pheromone effectiveness (Vanhove et al. 2015). Lures were further prepared by impregnating polyethylene vials (Length 26 mm, Diameter 8 mm, thickness 1.5 mm, Just Plastic Ltd., Norwich, United Kingdom) with 1 µL dichloromethane solution containing 100 µg or 33.3 µg of the pheromone blend 5 (with up to 45% of other geometric isomers, Table S1) (Vanhove et al. 2015) and a drop (~50 µL) of 2,6-di-tert-butyl-4-methylphenol (BHT) (10 mg/mL hexane) as antioxidant for this study (Vanhove et al. 2015). Lids of the vials were closed during entire experimental period and pheromone components were gradually released through the gaps between adjacent units of lids and vials.

2.3. Attract-and-kill stations

Delta traps (Trécé Pherocon trap IC) without sticky liners, on the inside as well as outer surfaces, were sprayed with cypermethrin solution at a concentration of 0.1% (v/v) at three-week intervals. Vials containing 100 µg (first season) or 33.3 µg (second season) of pheromone blend 5 (with up to 45% of other geometric isomers, Table S1) (Vanhove et al. 2015) were inserted and subsequently fixed into holes at the centers of the trap bottoms, so that the vials were inside the delta traps.

2.4. Experimental design

The 61-ha plantation was divided into an attract-and-kill subplot (21 ha, approximately 700 m × 300 m, in the east), a buffer plot (22 ha, approximately 770 m × 285 m, in the middle) and a standard CPB management plot (control plot) (18 ha, approximately 310 m × 580 m, in the west). In the standard CPB management and buffer plots, the standard plantation pest and disease chemical control schedule (application at 6-week intervals of ~110 mL per tree of a solution containing 190 mg of $Cu(OH)_2$ as fungicide and 110 µL of cypermethrin as insecticide) was continued, whereas in the attract-and-kill plot, cypermethrin was not applied on trees during the experimentation period.

Since *C. cramerella* predominantly swarms above the cocoa canopy, attract-and-kill stations were attached by ropes to nails on the top of wooden poles (5 m long) so that each trap was at least 50 cm above the cocoa canopy. Poles were fixed into 10 cm holes in the soil and positioned and tightened to a firm cocoa tree branch. In the 21-ha attract-and-kill plot, 170 attract-and-kill stations were thus distributed over the subplot in 17 rows of 10 stations (40 m between rows, 30 m between traps within one row). The effect of the attract-and-kill treatment on CPB-populations was evaluated by 9 monitoring traps (Delta Trécé Pherocon trap IC with 100 µg pheromone blend 5 (Vanhove et al. 2015), installed in the center of both the attract-and-kill and the standard CPB management plots. The latter traps were placed in 3 rows of 3 traps with 100 m between and within rows. Monitoring traps and poles were similar to those of the attract-and-kill stations except for sticky liners that were placed at the bottom of the monitoring traps, allowing to catch and subsequently count CPB-moths in each trap.

The first season was performed between November 14, 2014 and May 6, 2015, which coincided with the main cocoa harvest season of 2014–15. Because the detected effect of the attract-and-kill treatment on CPB-population levels were not translated into reduced pod damage with 100 µg pheromone loading in attract-and-kill stations, a second season was conducted with lower pheromone loadings (33.3 µg) in the attract-and-kill stations, based on the hypothesis that the response of the CPB-males might have been disrupted by the high pheromone concentrations applied in the first season, so that CPB-males were not able to locate the attract-and-kill stations and the monitoring traps either by camouflage, false trail following, sensory overload or by habituation, resulting in apparent catch number diminution, but ineffective population reduction. The second season was performed between October 20, 2015 and May 3, 2016, which coincided with the main cocoa harvest season of 2015-16.

Vanhove et al. (2015) found that all kinds of pheromone blends, including those with 47% geometric isomer impurities, remain effective for 8 weeks after installation in the field. Thus, in both the monitoring traps and attract-and-kill stations, vials with pheromone lure were replaced every 6 to 7 weeks (i.e. December 30, 2014, and February 10, and March 24, 2015 for the first season; December 10, 2015, and January 26, and March 22, 2016 for the second season).

2.5. Assessment of *C. cramerella* population

Monitoring traps were evaluated every week, following the method described by Vanhove et al. (2015). Each 4 week, the sticky liners were replaced because they lost stickiness by dust and dirt, making them inappropriate for CPB-moth counting. Captures were expressed per day by dividing CPB-moth count in each trap by the number of days that had passed since the last evaluation. The latter period was usually 7 days. However, in some cases, due to absence of researchers on the plantation, more time elapsed in between two evaluations.

2.6. Pod infestation and bean yield

Pod infestation and bean yield were evaluated 6 times during the first season (December 10, 2014, and January 1, February 11, March 6, April 7, and May 7, 2015) and 5 times during the second season (November 9 and December 23, 2015, and February 2, March 2, and May 5, 2016). For evaluation, both attract-and-kill and standard CPB management plots were subdivided in 3 equal subplots (with borders in the East-West direction). In each subplot, 100 ripe pods were harvested randomly so that a mixture of pods of each of the 7 cocoa clones was gathered. Pods were opened and classified according to infestation severity (Valenzuela et al. 2014) in which 4 categories (no damage, <33% of damaged pulp, between 33 and 66% of pulp damaged, and >66% of damaged pulp) were distinguished. Each pod with pulp showing CPB-infestation was not further considered in yield evaluation. Of all other pods, pulp with beans was extracted and pooled for all unaffected pods in the subplot and subsequently weighed. Wet bean weight data of the 3 subplots were averaged so that for each evaluation event, one value for the attract-and-kill and the standard CPB management plots, respectively, was obtained.

2.7. Statistical analyses

Captures of CPB were transformed by log10(x + 0.5) following Yamamura et al. (Yamamura et al. 2006) to remedy non-normality prior to statistical analysis using SPSS 22 (IBM Corporation, New York, NY). Within each week, differences in average captures per trap per day were assessed by the non-parametric Mann-Whitney U test. Kolmogorov-Smirnov test was used to evaluate normality of wet bean weight data distribution. Next, a T-test revealed significance of differences in wet bean weight between standard CPB management and attract-and-kill plots. Count data for each infestation severity category of each subplot were averaged, resulting in one value per evaluation event, for the attract-and-kill and the standard CPB management plots, respectively. Average count data were expressed as proportion of the total number of evaluated pods and subsequently transformed by arcsin(x). Normality of the transformed infestation data for all evaluation moments was evaluated by the Kolmogorov-Smirnov test. When data sets of both the standard CPB management and attract-and-kill showed a significant normal distribution, significance of difference between infestation data of standard CPB management and attract-and-kill plots was evaluated by a T-test. In the other case, the Mann-Whitney U test was applied (SPSS 22, IBM Corporation, New York, NY).

3. Results

3.1. First season

Attract-and-kill stations baited with 100 µg pheromone dose per vial as attractive source (December 2014–May 2015). During the whole experiment, average numbers of CPB-moths caught per trap per day were always higher in the standard CPB management plot as compared with the attract-and-kill plot (Figure 1). The differences were always significant ($P < 0.05$), except for December 12, 2014, January 13, and 20, 2015 and March 17, 2015. Highest average capture per trap per day in the standard CPB management plot was 2.44 (second week) after which average captures per trap per day fluctuated between 0.11 and 0.99. In the attract-and-kill plot, average CPB-capture per trap per day never exceeded 0.19.

At almost all evaluation events, the proportion of CPB-infested pods was higher in attract-and-kill plots than that in standard CPB management plots, for all infestation severity categories (Figure 2). Highest proportion of all pods with CPB-infestation symptoms (adding data of all 3 infestation severity

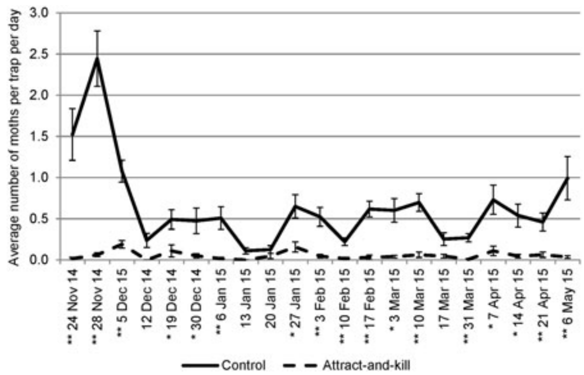

Figure 1. Moth count per trap per day (± standard error) in an experiment with 21 ha of cocoa plantation equipped with attract-and-kill stations with 100 µg of CPB-pheromone loading, monitored in the attract-and-kill plot and in an 18-ha standard CPB management plot (9 monitoring traps each, loaded with the same pheromone blend) between November 24, 2014 and May 6, 2015. Dates where significant differences between control and attract-and-kill monitoring trap catch numbers were observed are marked with *($P < 0.05$) or **($P < 0.01$).

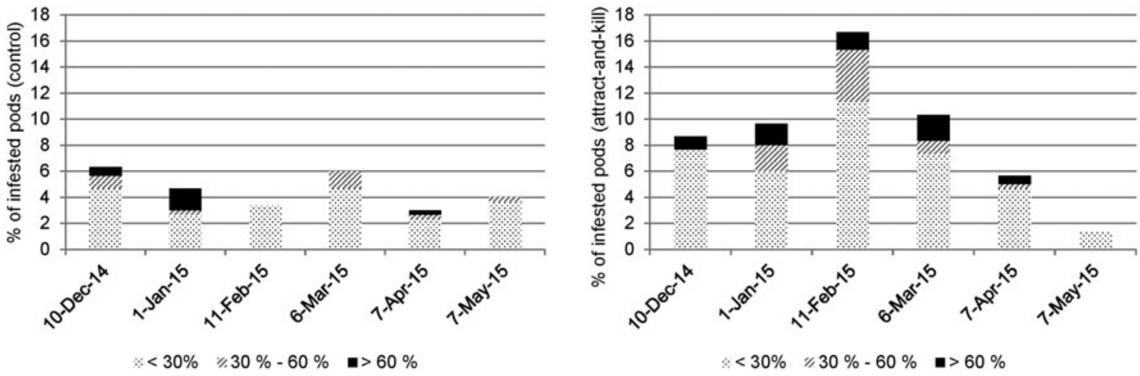

Figure 2. Percentage (%) of CPB pods in with < 30% (top), between 30 and 60% (middle) and > 60% (bottom) of pulp infested by CPB-larvae in a 21-ha attract-and-kill plot with 8 cypermethrin-treated killing stations per ha, loaded with 100 µg dose of CPB-pheromones and in an 18-ha standard CPB management plot (separated by a 22-ha buffer plot) between December 10, 2014 and May 7, 2015.

categories) was 17%, observed in the attract-and-kill plots on February 11, 2015. Average proportion of pods with CPB-infested pulp (sum of the three infestation categories) was 4.6% and 8.7% for pods collected at standard CPB management and attract-and-kill plots, respectively. No significant differences on proportions of infested pods were found between standard CPB management and attract-and-kill plots ($t = -1.937$; d.f. = 10; $P = 0.083$). Average number of beans and pulp extracted from 300 pods was 43.3 (± 1.6, standard error) kg in the standard CPB management plots as compared with 39.1 (± 0.7, standard error) kg in the attract-and-kill plots, with no significant differences between both yield figures ($t = 1.067$; d.f. = 10; $P = 0.311$).

3.2. Second season

Attract-and-kill stations baited with 33.3 µg pheromone dose per vial as attractive source (October 2015 – May 2016). Like the first season, average CPB-moth capture was always higher in standard CPB management plots than that in attract-and-kill plots (Figure 3). However, because of high variability in capture data between traps, catch differences between standard CPB management and attract-and-kill plots were only found to be significant ($P < 0.05$) for the evaluations done on October 28, November 19, and December 30, 2015 and on March 22, 2016. Highest average CPB-capture per trap per day was 0.80 and 0.39 for traps in the standard CPB management and attract-and-kill plots, respectively, both observed on April 8, 2016, but with no statistically significant (P > 0.05) differences between the two averages.

Unlike in the first season, during almost all evaluation events in the second season, the proportion of damaged pods was lower in attract-and-kill plots than that in standard CPB management plots, for each of the three infestation severity categories (Figure 4). Average proportion of pods with CPB-infested pulp (sum of the three infestation categories) was 8.1 and 3.7% for pods collected at standard CPB management and attract-and-kill plots, respectively, with significant ($t = 3.095$; d.f. = 6; $P = 0.021$) differences between the two averages. The average number of beans and pulp extracted from 300 pods was lower than that in the first season: 34.7 (± 3.5, standard error) kg in the standard CPB management plots and 37.1 (± 4.6, standard error) kg in the attract-and-kill plots. However, no significant differences between both yield figures ($t = -0.204$; d.f. = 8; $P = 0.905$) could be observed.

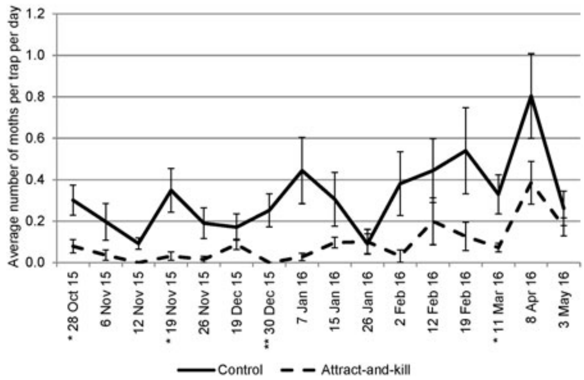

Figure 3. Moth count per trap per day (± standard error) in an experiment with 21 ha of cocoa plantation equipped with attract-and-kill stations with 33.3 µg dose of CPB-pheromone loading, monitored in the attract-and-kill plot and in an 18-ha standard CPB management plot (9 monitoring traps each, but loaded with 100 µg of the same pheromone blend) between October 28, 2015 and May 3, 2016. Dates where significant differences between control and attract-and-kill monitoring trap catch numbers were observed are marked with *($P < 0.05$) or **($P < 0.01$).

4. Discussion

In both experimental seasons, the insecticide-treated attract-and-kill stations seemed to be effective as they significantly ($P < 0.05$) reduced number of CPB-moths caught in monitoring traps. During the first season the reduction in catch numbers was not

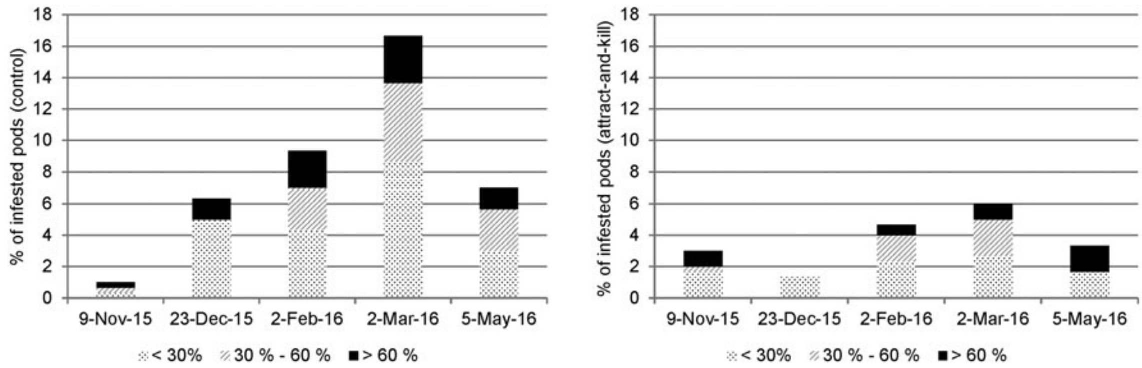

Figure 4. Percentage (%) of CPB pods in with <30% (top), between 30 and 60% (middle) and >60% (bottom) of pulp infested by CPB-larvae in a 21-ha attract-and-kill plot with 8 cypermethrin-treated killing stations per ha, loaded with 33.3 µg dose of CPB-pheromones and in an 18-ha standard CPB management plot (separated by a 22-ha buffer plot), evaluated between November 9, 2015 and May 5, 2016.

reflected in the evaluated proportion of CPB-affected pods or in cocoa yield data, our data indicated that the attract-and-kill technology was equivalent to the current standard CPM management using pesticide ($P = 0.082$). In the second season, attract-and-kill stations significantly ($P = 0.021$) reduced the proportion of CBP-infested pods (8.1% in standard CPB management as opposed to 3.4% in attract-and-kill plots). Although, in both seasons, extracted wet bean weight was not significantly ($P > 0.1$) different between attract-and-kill and standard CPB management plots, the attract-and-kill strategy was at least as good as the current CPB management approach using insecticide (standard CPB management plots were treated with $Cu(OH)_2$ as fungicide and cypermethrin as insecticide). It is worth to point out that no significant yield different between attract-and-kill and standard CPB management plots may be due to small plot size and low density of attract-and-kill station. It would be helpful to carry out more studies at large-scale cocoa plantation and increase the density of attract-and-kill station. The two seasons were performed in the main harvest seasons of two consecutive years (2014-15 and 2015-15) and differed only in dose of pheromone blend in the vials attached to the attract-and-kill stations (100 µg and 33.3 µg per vial in the first and second season, respectively). The observed discrepancy between the lower CPB-moth catch in the monitoring traps and the undetectable effects on pod loss and wet bean yield in the first season could possibly be explained by the high (100 µg per vial) dose of the pheromone blend in the attract-and-kill stations. Just as would be the case in a mating disruption control strategy, where high pheromone concentrations disrupt the signalling of CPB-females by camouflage, false trail following, sensory overload, or habituation, so that CPB-males can no longer locate them, CPB-lures in the attract-and-kill stations of the first season might have disrupted CPB-males to the extent where they could no longer locate neither the attract-and-kill stations nor the monitoring traps (Witzgall et al. 2010). Thus, the insecticide sprayed on the attract-and-kill stations would not have been effective in reducing the CBP population. The apparent population reduction as shown by the lower numbers of CPB-males caught by the monitoring traps would thus have been caused by the same disruption of the CPB-male response to pheromones from the 100 µg vials.

In this study, we have applied our pheromone blend in polyethylene vials attached to delta traps. However, other pheromone dispensing methods can be applied in attract-and-kill strategies. The most frequently cited method is the combined application of pheromones (or other attractants) with an insecticide in a viscous paste, typically applied as 50–100 µL droplets (Charmillot et al. 2000; Krupke et al. 2002; Mansour 2010; Stelinski and Czokajlo 2010; Campos and Phillips 2014). Other methods include pheromones impregnated onto wax panels (Campos and Phillips 2014) and rubber septa (Hossain et al. 2008), or pheromones blended in soybean or palm stearin fat pellets (Krupke et al. 2002).

The number of sex pheromone point sources, which is key to the ability of insect males to locate females (Krupke et al. 2002; Witzgall et al. 2010), also varies between the different experiments reported in literature. In attract-and-kill control of the citrus leaf miner (*Phyllocnistis citrella*), optimum viscous pheromone droplet application number was found to be 3000 per ha (Stelinski and Czokajlo 2010). The same densities were also reported as effective in attract-and-kill control of codling moth (*Cydia pomonella*) in apple orchards in Canada (Krupke et al. 2002), Switzerland (Charmillot et al. 2000) and Syria (Mansour 2010). In the control of *Carphilus spp.* (Coleoptera: Nitidulidae) in stone fruit in Australia, Hossain et al. (2008) showed that attract-and-kill station densities as low as 2 per ha could be effective.

Apart from cypermethrin, other insecticides have also been successfully applied in attract-and-kill research. They include the pyrethroid permethrin at a concentration of 6% (Charmillot et al. 2000; Mansour 2010; Stelinski and Czokajlo 2010; Campos and Phillips 2014), and the organophosphate dichlorvos (Hossain et al. 2010). In an attract-and-kill experiment performed in closed containers, Lopes et al. successfully tested the effectiveness of the entomopathogenic fungus *Beauveria bassiana* against the banana weevil *Cosmopolites sordidus* (Coleoptera: Curculinoidae), albeit with low mortality levels (21.7% weevil individuals exposed pheromone + fungus impregnated soybean fat pellets) (Lopes et al. 2014).

5. Conclusions

Applying an attract-and-kill strategy to a 21-ha cocoa plot, using 8 cypermethrin-treated attract-and-kill stations per ha, containing polyethylene vials with 33.3 µg dose of an impure CPB-pheromone blend successfully reduced the number of CPB-infested cocoa pods in our second season comparing with the current CPB management approach using insecticide. It indicates that attract-and-kill strategy is more feasible and superior over the conventional synthetic pesticide treatment in CPB control, resulting reduction of the insecticide applied to the environment. Given the economic impact of *C. cramerella* on the cocoa sector, and based on our findings, the attract-and-kill strategy deserves further exploration as a cost-effective, healthy and environmentally-friendly CPB-control measure. Further research should be performed on larger cocoa estates or on different estates in a given area with comparable CPB-infestation levels to enable replication of experiments that will reduce the effect of confounding factors such as soil properties, shade levels, or cocoa management practices such as pruning, fertilization and chemical pest control treatments.

In our research, we have shown that attract-and-kill stations containing 33.3 µg dose of impure sex pheromone blend are more effective than the same stations with vials containing 100 µg of the same pheromone blend, possibly due to reduction of mating disruption effect to CPB-males by the stations with lower sex pheromone loading. The density of attract-and-kill stations (8 per ha) was arbitrarily applied in our experiments. More research, testing a broader range of pheromone loadings, different killing station densities, and pheromone blends in combination with other insecticides in viscous formulations in large-scale, is needed to develop the attract-and-kill strategy into an efficient, safe, and environmentally-friendly CPB-control method. In addition, pheromone dispensers and attract-and-kill stations could be easily installed and removed from the crop field. Fine-tuning of the attract-and-kill strategy against CPB can result in the identification of effective and economically viable programs based on natural products to be delivered to the cocoa industries and commercial companies in Southeast Asia, thereby reducing threats to natural ecosystems and human health caused by overuse of conventional synthetic pesticides.

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Disclosure statement

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