Jurnal Entomologi Indonesia
p-ISSN: 1829-7722 e-ISSN: 2089-0257
Terakreditasi Kemenristekdikti: 105/E/KPT/2022

November 2024, Vol. 21 No.3, 184–199
Online version: https://jurnal.pei-pusat.org
DOI: https://doi.org/10.5994/jei.21.3.184

Management of fall armyworm, *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) in maize (*Zea mays* L.) in Indonesia and Thailand via mating disruption

Pengendalian ulat grayak, *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) pada jagung (*Zea mays* L.) di Indonesia dan Thailand dengan gangguan kawin

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(diterima Agustus 2024, direvisi Oktober 2024, disetujui November 2024)

ABSTRACT

The fall armyworm, *Spodoptera frugiperda* (Smith), has been problematic in Southeast Asia since its invasion in 2019. Fall armyworm management in these areas largely depends on synthetic insecticide application, and alternative management practices are very few and impractical. The demand for new and more sustainable tools for managing this pest has increased. In this study, we tested the mating disruption (MD) efficacy of fall armyworm sex pheromone in low-density polyethylene dispensers containing 2.5 g of blended active ingredients, (Z)-9-tetradecen-1-yl acetate (Z9-14Ac) and (Z)-11-hexadecen-1-yl acetate (Z11-16Ac) in a ratio of 87:13. The primary objective was to evaluate the optimal density of the dispensers/ha and understand the benefits of MD in reducing the damage caused by fall armyworm and associated insecticide applications as compared to conventional growers' practices in Indonesia and Thailand. Research was conducted at 16 locations across Indonesia and Thailand in 2020 and 2021 in 9-ha treatment plots and compared to conventional growers practice. Trap reduction, a measure of MD, was significantly higher (74–90%) with 30 dispensers/ha than with non-dispenser areas, suggesting high levels of mating suppression. MD's primary benefit is damage reduction, where 30 dispensers/ha reduced damage caused by fall armyworm larvae by 34–35% while simultaneously enabling a greater than 50% reduction in insecticide usage compared to the conventional growers' practice. Our results show the effectiveness and feasibility of MD using pheromones as an essential management tactic for fall armyworm. These results represent a potential step towards more efficacious and sustainable pest management in Southeast Asia.

Key words: fall armyworm, Indonesia, mating disruption, pheromones, *Spodoptera frugiperda*, Thailand

ABSTRAK

Ulat grayak *Spodoptera frugiperda* pada jagung telah menjadi masalah di Asia Tenggara sejak invasinya pada tahun 2019. Pengendalian ulat grayak di wilayah ini sebagian besar bergantung pada aplikasi insektisida sintetik, sedangkan pengendalian alternatif sangat sedikit dan tidak praktis.

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Permintaan alat pengendalian baru dan yang lebih berkelanjutan untuk hama ini telah meningkat dalam beberapa tahun terakhir. Dalam penelitian ini, kami menguji efektifitas gangguan perkawinan (MD) dari feromon seks ulat grayak dalam dispenser polietilen berdensitas rendah yang mengandung 2,5 g bahan aktif campuran, (Z)-9-tetradecen-1-yl asetat (Z9-14Ac) dan (Z)-11-hexadecen-1-yl asetat (Z11-16Ac) dalam rasio 87:13. Tujuan penelitian adalah untuk mengevaluasi kepadatan optimal dispenser/ha dan memahami manfaat MD dalam mengurangi kerusakan yang disebabkan oleh ulat grayak beserta aplikasi insektisida terkait dibandingkan dengan pengendalian petani konvensional di Indonesia dan Thailand. Penelitian dilakukan di enam belas lokasi di Indonesia dan Thailand pada tahun 2020 dan 2021 pada plot perlakuan seluas 9 ha dan dibandingkan dengan praktik petani konvensional. Pengurangan tangkapan sebagai pengukur MD, secara signifikan lebih tinggi (74−90%) pada plot 30 dispenser/ha dibandingkan dengan area tanpa dispenser, mengindikasikan tingkat penekanan perkawinan yang tinggi. Manfaat utama MD adalah pengurangan kerusakan, plot 30 dispenser/ha mengurangi kerusakan ulat grayak sebesar 34−35% sekaligus mengurangi penggunaan insektisida lebih dari 50% dibandingkan dengan praktik petani konvensional. Hasil penelitian menunjukkan efektivitas dan kelayakan MD dengan feromon sebagai taktik pengendalian penting untuk ulat grayak. Hasil ini merupakan langkah potensial menuju pengendalian hama yang lebih efektif dan berkelanjutan di Asia Tenggara.

Kata kunci: feromon, gangguan kawin, Indonesia, *Spodoptera frugiperda*, Thailand, ulat grayak

INTRODUCTION

The maize fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a notorious crop pest that originated from tropical and subtropical America (Sparks 1979). However, FAW has not just invaded but resiliently established colonies in more than 70 countries across Africa, Asia, and Australia, demonstrating its global reach and impact (Tay et al. 2023). Its highly adaptive strategies, polyphagous nature, short life cycle, migration patterns, high reproductive potential, and increased capability to adapt to new environments have contributed to its relentless spread to various regions outside its native range (Sharanabasappa et al. 2018; Dharmayanti et al. 2022) where maize, (*Zea mays* L.) is an important staple food crop. For instance, in Thailand, the Department of Agriculture (DoA) detected FAW in a few sub-districts of the Kanchanaburi and Tak Provinces along the border of Myanmar in December 2018 (Chaireunkaew et al. 2022). Similarly, FAW reached West Sumatra, Indonesia, in March 2019 (Trisyono et al. 2019; Sartiami et al. 2020). In the same year, FAW quickly invaded other provinces on Sumatra Island (Hutasoit et al. 2020), Java (Rizali et al. 2021) and Bali Islands (Supartha et al. 2021), spanning hundreds of kilometers across the Indonesian archipelago. Since its establishment in Thailand and Indonesia, FAW has wreaked havoc and caused substantial economic damage to maize fields throughout the Asia–Pacific region (De Groote et al. 2020).

The larvae of *S. frugiperda* are ferocious herbivores that can destroy maize plants as they feed on whorl leaves, leaving holes or until only the vein, epidermal layer, and stems are stranded off maize plants. Furthermore, they burrow through the husk and feed on the kernels, causing damage to the ear (Sarkowi & Mokhtar 2021). Initially, insecticide label expansion was the only control measure used to curb the outbreak. Massive application of synthetic insecticides and government subsidies have become an emergency control strategy for managing FAW in Thailand and Indonesia. Because FAW is an invasive pest, insecticide resistance has also been applied to new regions (Tay et al. 2023). Gutiérrez-Moreno et al. (2019) reported that FAW developed resistance to at least 29 active ingredients of insecticides via six modes of action. Considering the unwanted negative impacts of synthetic insecticide application on natural enemies, the environment, and human health, there is an urgent need for more sustainable management strategies for FAW.

One sustainable pest management method for managing FAW is mating disruption (MD) via sex pheromones (Witzgall et al. 2010; Lopez-Urquidez et al. 2023). MD prevents reproduction in the targeted pest. Communication between males and females is disturbed through competitive and non-competitive mechanisms, resulting in mating failure (Rizvi et al. 2021). MD has been studied and has been successfully implemented in various crops. Recently, it was introduced to manage yellow rice stemborers in Indonesia

(Iqbal et al. 2023). Mating disruption in FAW with pheromones has been well studied in Mexico and has been shown to increase the biodiversity of natural insect enemies (Lopez-Urquidez et al. 2023). Preventing FAW reproduction is critical, as they have high fecundity with three generations per growing season in warm tropical conditions, such as Indonesia and Thailand (Russianzi et al. 2021).

One of the historical limitations of mating disruption is the high cost of synthesizing sex pheromones (Holkenbrink et al. 2020). In recent years, catalysis-based pheromone manufacturing processes that require fewer synthetic steps and are more sustainable have been developed (Wampler et al. 2021). This innovation has resulted in more affordable pheromone-based products for use in row crops. This technology can be used in a wide field area to achieve high efficacy of MD in managing FAW. Mating disruption technology for FAW has been registered in Mexico (Lopez-Urquidez et al. 2023) and Brazil (Schirmer et al. 2023) and is being used commercially. These are considered safer pest management under the biopesticide product category (Prasanna et al. 2021. Therefore, MD has high potential as a sustainable strategy to integrate with FAW pest management and be evaluated in Asia.

The main objective of these trials was to understand the potential of MD in terms of damage reduction, insecticide application reduction, and yield protection. The results will allow us to understand the potential inclusion of pheromone-based MD compared to conventional growers' practices, which primarily involve insecticide applications in managing FAW in corn.

MATERIAL AND METHOD

Field trial locations

Field trials were conducted for two consecutive years, starting in November 2020 in Indonesia and the March 2021 planting season in Indonesia and Thailand. Sixteen trials were conducted across the Java and Sumatra islands of Indonesia and Thailand's key maize-producing provinces. The trials will be completed by the end of 2021. We collaborated with more than 500 growers to procure nearly 600 ha of land for these trials. The details of the locations are presented in Table 1.

Materials

These large-scale studies evaluated the performance of slow-release low-density polyethylene (LDPE) dispensers filled with 2.5 grams of blended FAW sex-pheromone active ingredients, (*Z*)-9-tetradecen-1-yl acetate (Z11-16Ac), and (*Z*)-11-hexadecen-1-yl acetate (Z11-16Ac) in a ratio of 87:13. Dispensers were installed on thin bamboo sticks with a cable tie 0.5 m above the ground. Pheromone bucket traps were used to trap the male moths and to evaluate MD via trap reduction. Commercially available FAW lures with similar blend ratios and bucket traps were purchased from Pherobio Technology Company, Ltd., Beijing, China. FAW lures were installed in the traps at 0.5 to 0.7m and replaced every 20 days. Both dispensers and traps were installed as soon as the maize germinated after sowing, approximately one week after sowing. The sowing of all treatments at each location was completed within ten days to achieve a similar plant stage. Similar maize hybrids were planted in both pheromone treatment plots, pheromone foundational practice (PFP) and conventional grower's practice (CGP), at each location to maintain uniformity.

Experimental design and plot layout

Each trial location consisted of two treatments: pheromone foundational practice (PFP), treatment with dispensers containing blended FAW sex-pheromone active ingredients, and conventional growers' practices (CGP), treatment based on common growers' practices to manage FAW. To ensure that the small plot size did not negatively affect the potential benefits of MD, the PFP treatment plots were 9-ha. The internal dose rate optimization of FAW dispensers tested with the same parameters as in these experiments, at ten dispenser increment levels from zero to 50 dispensers/ha revealed that a range of 20 to 40 dispensers/ha was an appropriate density (Provivi, internal data 2020). Since the minimum area treated is unnecessary for CGP or control, a 2-ha plot in the same area was demarcated. We reduced the edge effects wherever possible by selecting near-square-shaped PFP and CGP plots. A 200–

Table 1. The number of locations where field research was conducted to understand the performance of mating disruption to manage FAW (fall armyworm, *Spodoptera frugiperda*) in maize. Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand

Country	Province	District	Village	Year	Season occurrence	Planting season	Plot size/ Treatment
Indonesia	East Java	Lamongan	Paciran	2020	November 2020–February 2021	Wet season	9
Indonesia	East Java	Tuban	Tambakboyo	2020	November 2020–February 2021	Wet season	9
Indonesia	East Java	Gresik	Lowayu	2020	November 2020–February 2021	Wet season	9
Indonesia	South Sumatra	Lampung	Adiluwih	2020	November 2020–February 2021	Wet season	9
Indonesia	South Sumatra	Lampung	Tanjung-Bintang	2020	November 2020–February 2021	Wet season	9
Indonesia	East Java	Jember	Grenden Puger	2021	March 2021–June 2021	Dry season	9
Indonesia	East Java	Situbondo	Karangasem	2021	March 2021–June 2021	Dry season	9
Indonesia	East Java	Jember	Kemuning	2021	March 2021–June 2021	Dry season	9
Indonesia	East Java	Situbondo	Patek	2021	June 2021–October 2021	Dry season	9
Indonesia	East Java	Nganjuk	Sonobekel	2021	June 2021–October 2021	Dry season	9
Indonesia	East Java	Situbondo	Tanjung Kamal	2021	June 2021–October 2021	Dry season	9
Indonesia	East Java	Situbondo	Wringinanom	2021	June 2021–October 2021	Dry season	9
Thailand	Chiangmai	Maejam	Maejam	2021	May 2021–October 2021	Wet season	9
Thailand	Uthaithani	Sawang Arom	Sawang Arom	2021	May 2021–October 2021	Wet season	9
Thailand	Nakhon Sawan	Takhfa	Takhfa	2021	May 2021–October 2021	Wet season	9
Thailand	Nakhon Sawan	Takhli	Takhli	2021	May 2021–October 2021	Wet season	9

500 m buffer was maintained between the PFP and CGP plots to minimize the drift of pheromones and contamination of treatments. All treatment plots were at least 100 m from a light source to avoid interference towards pheromone traps. A pheromone trap was installed in the middle of each hectare for each treatment. Additionally, to monitor the FAW population in the surrounding areas, four to six additional pheromone traps were installed in all directions of the trial location while maintaining at least 200 m from the PFP plots.

Need-based insecticide applications

The PFP treatment plot was sprayed with approved insecticides at a labeled rate when a threshold of 20% of the damage was noticed, with damage defined as a Davis damage severity scale (Davis et al. 1992) of 3 out of 9 on the top three whorl leaves. For the CGP treatment, there was no restriction on insecticide application, and they were made according to each grower's practice.

Data collection

Moth capture. To understand trap reduction (MD), starting from the installation, moth capture assessments were made every seven–ten days until harvest (~90 days crop). At each assessment, the male FAW moths caught in the traps were counted and the traps were reset with water mixed with non-odor detergent or oil.

Damage assessments. Vegetative damage assessments were conducted at regular intervals, starting seven days after the installation of dispensers in the field. Damage assessments were performed by scouting the damage severity caused by the FAW larvae. Damage in the vegetative stage was assessed on the top three whorl leaves based on the Davis damage severity scale of 0 to 9, where a higher severity denotes more significant damage by FAW larvae (Davis et al. 1992). Damage in the vegetative stages was assessed until the tasselling stage at seven-day intervals until 49 days after planting, with a damage rating of 20 plants per transect and 15 to 20 transects/ha. The distance between sampling points was 17 m.

Insecticide application. Insecticide application was recorded in both PFP and CGP treatment plots. The type of insecticide and dose rate were also recorded.

Data analysis

Trap reduction as a measure of mating disruption. The reduction in adult (male) moth trap counts in the PFP versus CGP is a proxy for mating disruption. Trapping reduction is the percentage decrease in moth captures in PFP traps compared to non-dispenser areas, such as CGP. Moth counts were modeled as an overdispersed Poisson variable as a function of pheromone treatment, time, and spatiotemporal random effects to account for the inherent correlations within and between trials. A hierarchical Bayesian framework was used to allow for the expected nonlinear, nonincreasing trend in trapping reduction over time. The nonlinear function used to model the trapping reduction over time is highly flexible and allows trapping reduction associated with the pheromone treatment to remain constant for many days before the expected decrease (at some point in time, all dispensers will eventually run out of pheromone active ingredient and will stop working), and then plateau at no pheromone effect, that is, no trapping reduction related to the pheromone treatments. Alternatively, if no trapping reduction is observed, the model allows this possibility. The model was fitted in MATLAB (Mathworks, Inc. 2021) using customized sampling algorithms.

Damage reduction as a result of mating disruption. This analysis aimed to determine whether there was a significant reduction in leaf damage in plots under the PFP treatment compared to plots under the CGP treatment. Damage reduction is the percentage decrease in the damage scale in PFP fields compared to non-dispenser areas such as CGP. The damage rating scale per sampling point was modeled as an over-dispersed ordinal variable as a function of pheromone treatment and spatiotemporal random effects to account for the inherent correlations within and between trials. The model was similar to a generalized linear mixed model (GLMM), but with spatiotemporal random effects defined as in the trap count model and not based on qualitative groupings. Again, a hierarchical Bayesian model framework was used, and the model was fitted through a customized slice-sampling algorithm in MATLAB (Mathworks, Inc. 2021) using customized sampling algorithms.

Insecticide usage reduction with mating disruption. The collected data from several insecticide spray applications in the PFP and CGP plots were analyzed by comparing them with a paired t-test in MATLAB (The Mathworks, Inc. 2021).

RESULTS

Trap reduction as a measure of mating disruption

Lower trap captures in the PFP than in the CGP indicate higher mating disruption. In the absence of pheromone dispensers, normal moth captures occur when pheromone traps are installed. FAW moths captured in CGP with no pheromones (control) in Indonesia's wet season 2020 trial locations ranged from six to 30 months per trap. East Java had a higher moth pressure than South Sumatra (Figure 1). Seasonal variation in the FAW moth pressure differed as moth pressure in control plots was higher (up to 60 moths/trap/day) in the northern and western parts of East Java (Situbundo and Nganjuk regencies) than in the southern part of the Jember regency (two to four moths/trap/day). Compared to Indonesia, four locations across the central and northern parts of Thailand captured fewer moths in the control plots, one to two moths/trap/day (Figure 2).

The analysis of trap reduction in Indonesia's wet season 2020, as a measure of mating disruption, concluded that all PFP treatments, 20, 30, and 40 dispensers/ha, significantly reduced trap captures compared to control plots (Figure 3). The analysis of moth captures in the five locations showed strong evidence of trapping reduction in all PFP treatments. The maximum trapping reduction was observed with 40 dispensers/ha, with a median trapping reduction of 88% (79–93% at 95% CI) over the entire 90-day season. However, 20 and 30 dispensers/ha treatments also provided season-long trapping reduction, with a median trapping reduction of 69% (47–86% at 95% CI) and 74% (60–85% at 95% CI), respectively (Table 2).

The trapping results from the 2021 season, from seven locations in Indonesia and four locations in Thailand, showed a significant reduction in trapping in 30 and 40 dispensers/ha treatment plots (Figure 3). A median trapping reduction of 90% (75–93% at 95% CI) and 93% (87–96% at 95% CI) was observed for 30 and 40 dispensers/ha treatments as season-long trapping reduction. The 20 dispensers/ha treatment also showed a season-long trapping reduction, with a median of 69% (Table 2). However, wider credible intervals were observed in the 20 dispensers/ha (47–86% at 95% CI) treatment, showing less consistent disruption during the cropping season. Both the 30 and 40 dispensers/ha treatments led to significantly higher

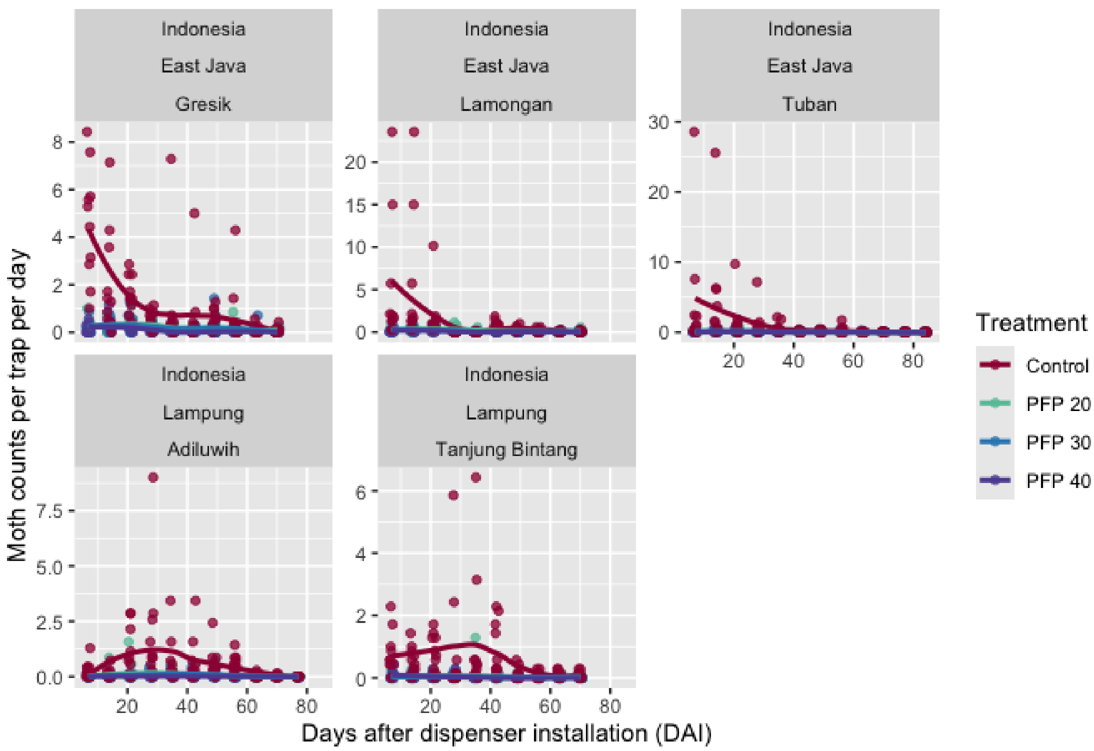

Figure 1. Moth captures in the traps placed in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) to demonstrate trap reduction as a result of mating disruption. Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season of 2020.

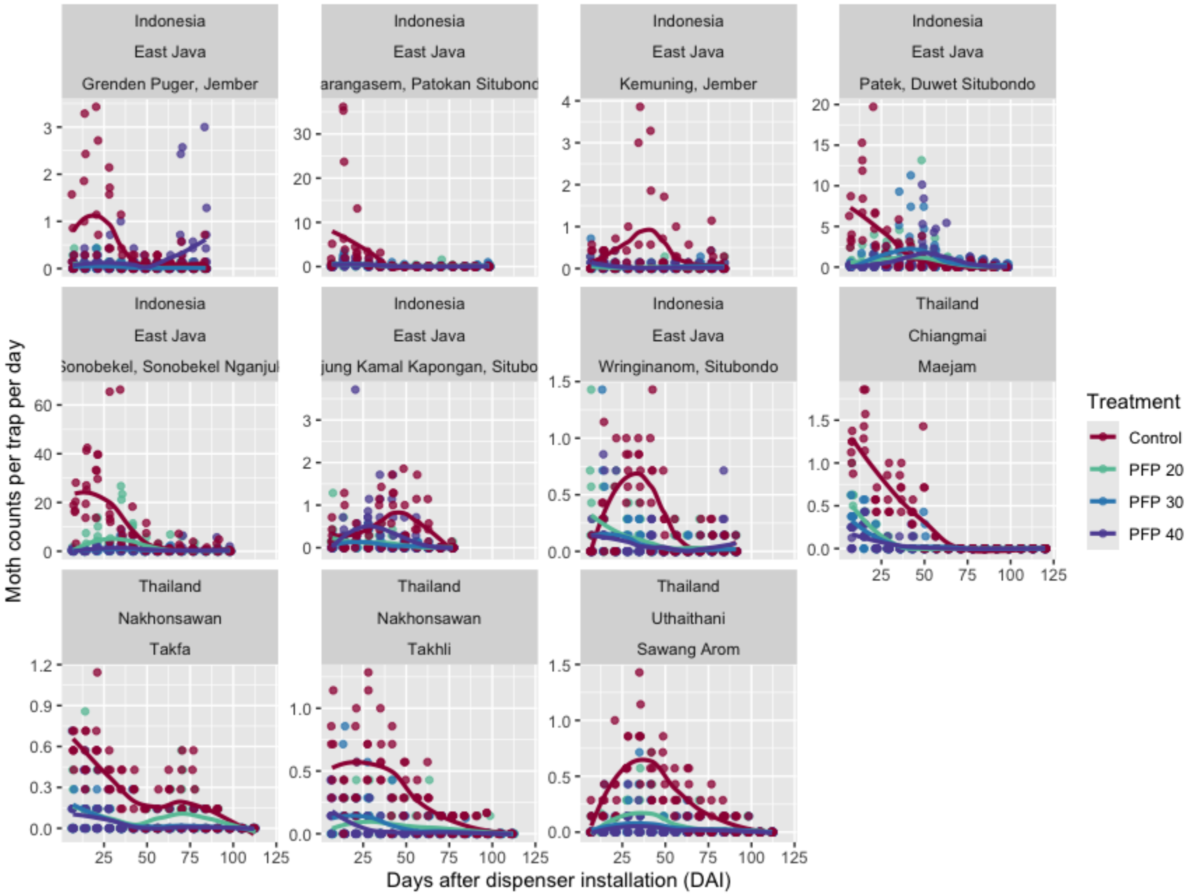

Figure 2. Moth captures in the traps placed in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) to demonstrate trap reduction as a result of mating disruption. Seven locations are distributed in East Java (Indonesia) and four across Thailand in the 2021 maize production season.

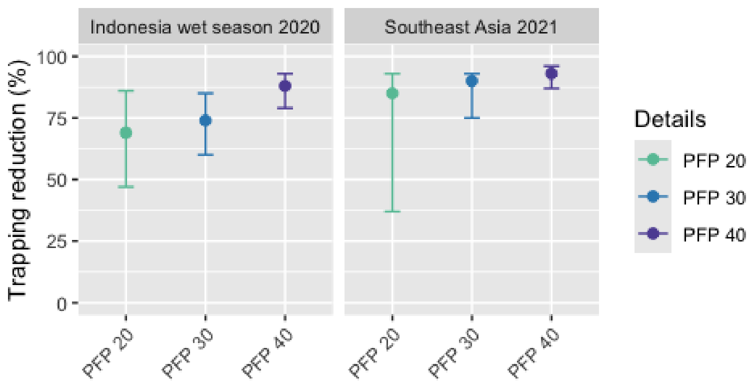

Figure 3. Overall, season-long average trapping reduction due to mating disruption in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha compared to no-pheromone control plots (CGP–conventional growers practice). Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand.

trapping reductions than the 20 dispensers/ha treatments (P < 0.05; Bayesian P-value).

Damage reduction as a measure of mating disruption

Data analysis was performed on the damage caused by the larval population of fall armyworms among various pheromone treatments collected on the Davis Scale, 0 to 9, where a higher scale corresponds to more significant damage. Figure 4 shows the damage to the vegetative stages of maize (up to 45–50 days after planting) in the wet season of Indonesia in 2020. All five locations had an average score ranging between 0 and 5, whereas Southeast Asia 2021 had a higher range of average scores between 0 and 7 (Figure 5). Two locations in Thailand (2021), Takhi, Nakhonsawan, and Sawang Arom, Uthaithani, experienced

Table 2. Overall season-long (90 days) average trapping reduction due to mating disruption in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha compared to no-pheromone plots, displayed as median trap reduction, upper and lower credible intervals (95% CI). Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand

Locations & Seasons	Treatment	Median TR*	TR*: lower 95% credible interval	TR*: upper 95% credible interval
Indonesia wet season 2020	PFP 20	69	47	86
Indonesia wet season 2020	PFP 30	74	60	85
Indonesia wet season 2020	PFP 40	88	79	93
Southeast Asia 2021	PFP 20	85	37	93
Southeast Asia 2021	PFP 30	90	75	93
Southeast Asia 2021	PFP 40	93	87	96

*TR: trapping reduction in PFP compared to CGP.

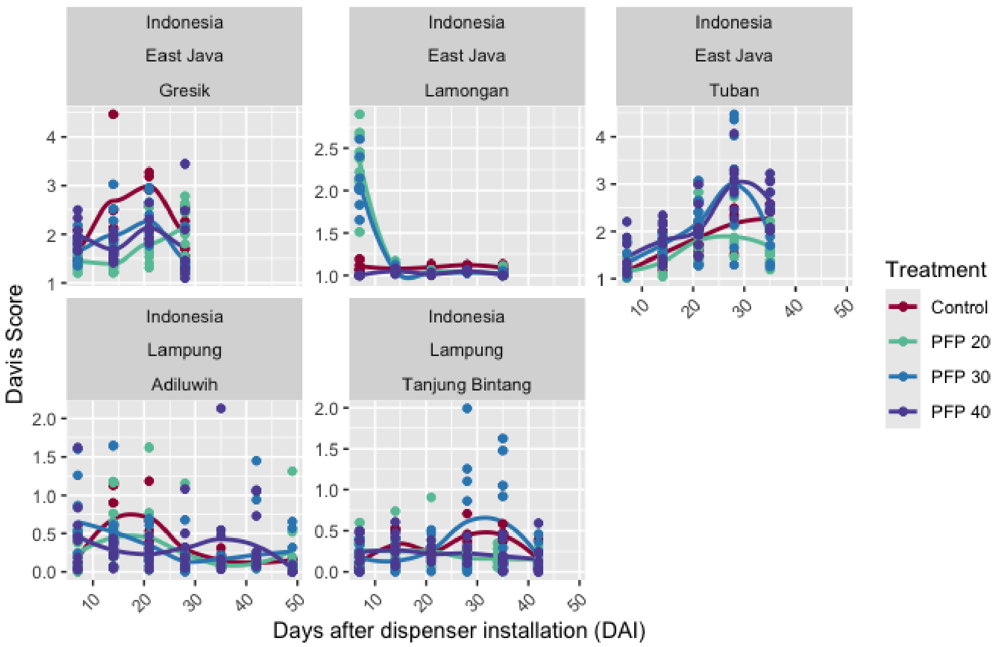

Figure 4. Larval damage caused by FAW (fall armyworm, *Spodoptera frugiperda*) on the vegetative stages of maize (up to 45 to 50 days after planting) measured on a Davis scale of 0 to 9 (9 being greater damage) in the pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) as a result of mating disruption. Each data point is the average Davis score associated with a transect. Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season of 2020.

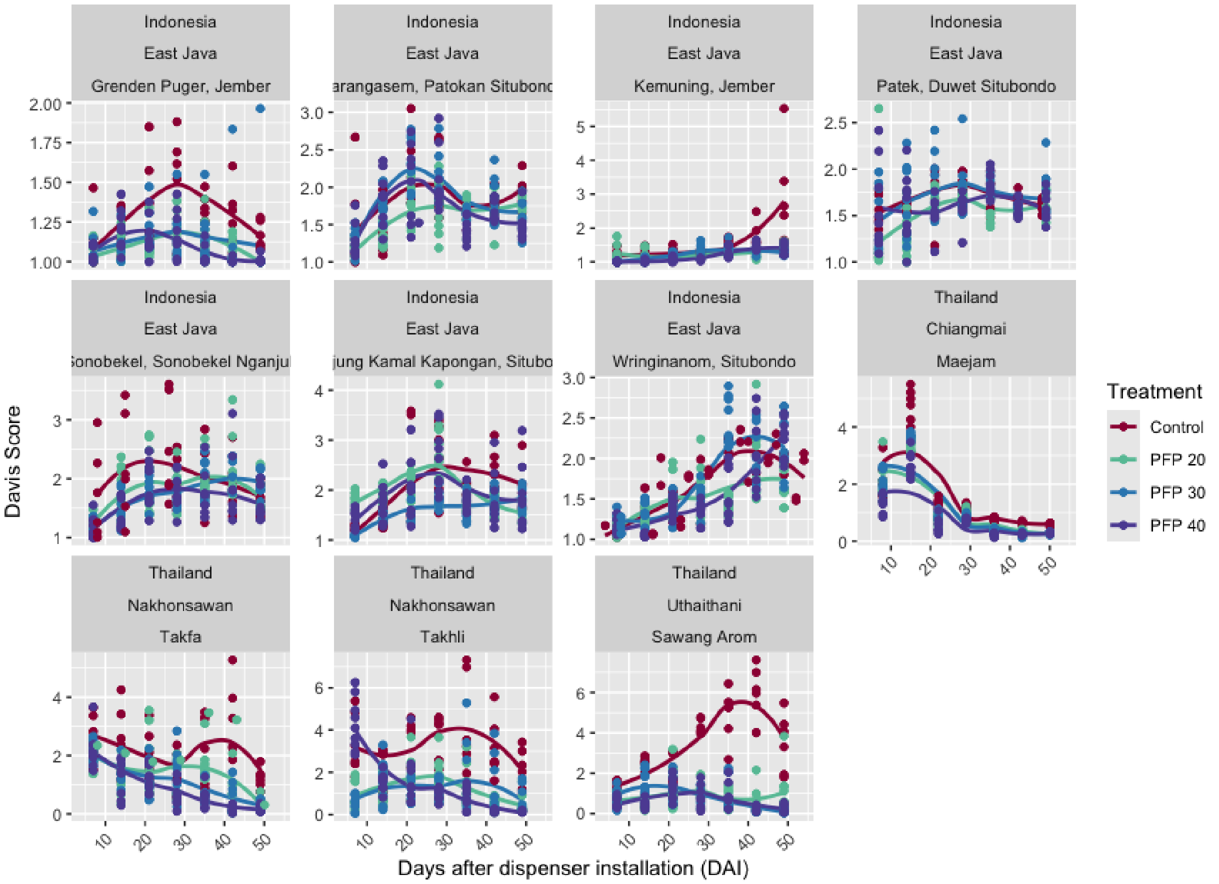

Figure 5. Larval damage caused by FAW (fall armyworm, *Spodoptera frugiperda*) on the vegetative stages of maize (45 to 50 days after planting) measured on a Davis scale of 0 to 9 (9 being greater damage) in the pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) as a result of mating disruption. Each data point is the average Davis score associated with a transect. Seven locations are distributed in East Java (Indonesia) and four across Thailand in the 2021 maize production season.

more severe damage than the others. At various locations, the damage in the pheromone-treated plots was lower than that in the control plots. We also noticed that the 30 and 40 dispensers/ha treatments had lower damage ratings than the 20 dispensers/ha and CGP treatments did. The severity of the damage, shown as the proportion of plants reaching various levels of the Davis Scale, is presented in Figures 6 and 7.

The severity of the damage, combined for five locations in Indonesia during the wet season of 2020, showed that the control plots, even when applied with more insecticide treatments, often reached the economic threshold of damage (20% of plants reaching more than three on the Davis Scale). However, the severity of damage in the pheromone treatments was lower, despite fewer insecticide sprays (Figure 6). Damage severity at 11 locations across Indonesia and Thailand (2021) showed a similar trend, with a more significant proportion of plants reaching severe damage in the control plots (Figure 7). We also noticed that the PFP 20 dispensers/ha treatment caused slightly more damage than the 30 and 40 dispensers/ha treatments.

Overall, damage reduction analysis from five locations in Indonesia during the wet season of 2020 showed that all PFP treatments (20, 30, and 40 dispensers/ha) worked very well, providing a median damage reduction of 35, 34, and 39% over the control plots, respectively (Table 3). The differences between the PFP treatments were not statistically significant ($P > 0.05$; Bayesian P-value) (Figure 8). For Southeast Asia's 2021 damage results, all treatments significantly reduced the damage compared with the control

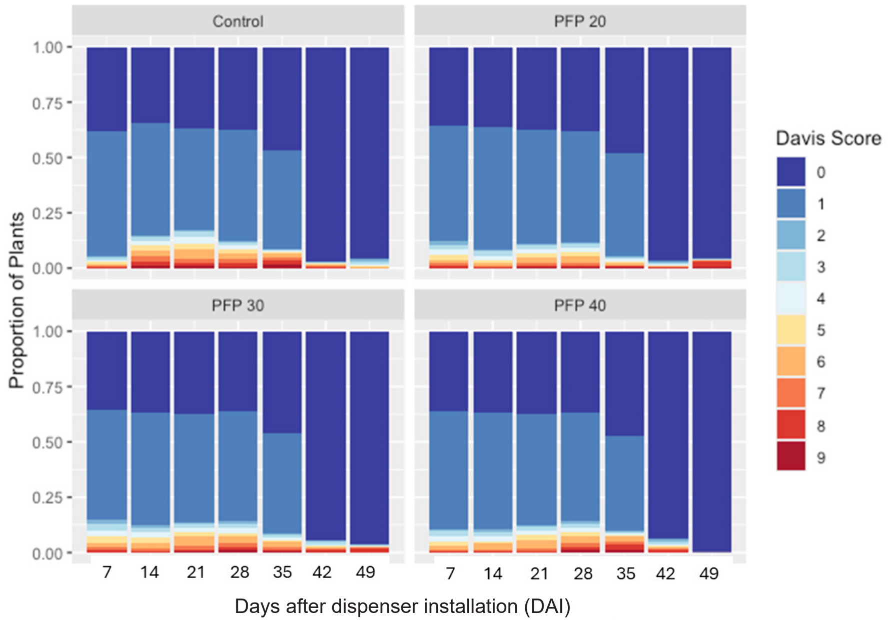

Figure 6. The severity of damage shown as proportion of damaged plants sampled due to FAW (fall armyworm, *Spodoptera frugiperda*) on the vegetative stages of maize (45 to 50 days after planting) measured on a Davis scale of 0 to 9 (9 being greater damage) in the pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) as a result of mating disruption. Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season of 2020.

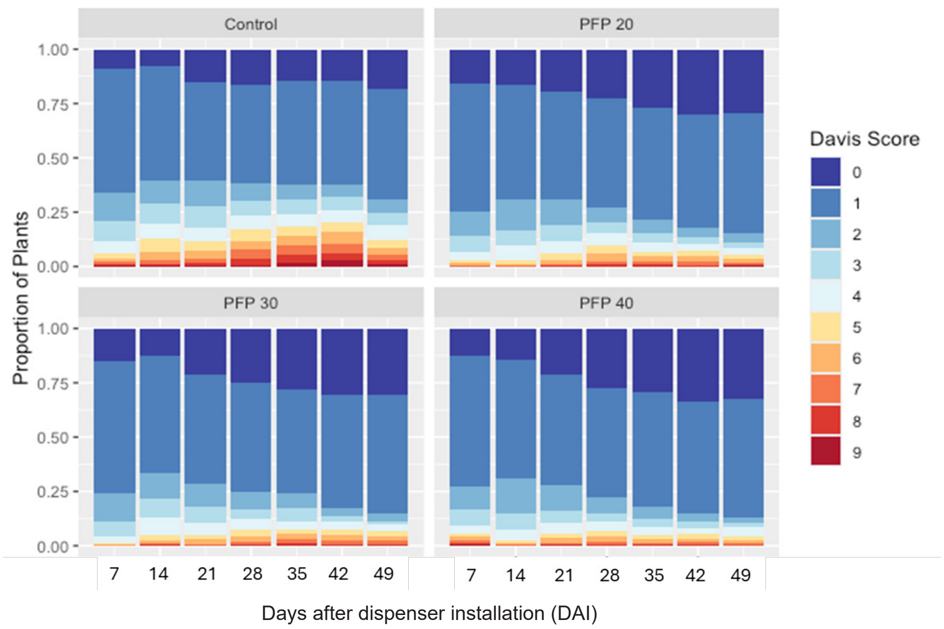

Figure 7. The severity of damage shown as proportion of damaged plants sampled due to FAW (fall armyworm, *Spodoptera frugiperda*) on the vegetative stages of maize (45 to 50 days after planting) measured on a Davis scale of 0 to 9 (9 being greater damage) in the pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha as compared to no-pheromone control plots (CGP–conventional growers practice) as a result of mating disruption. Seven locations are distributed in East Java (Indonesia) and four across Thailand in the 2021 maize production season.

Table 3. Overall damage reduction on the vegetative stages of maize (45 to 50 days after planting) due to mating disruption in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha compared to no-pheromone control plots (CGP–conventional growers practice). Displayed as median damage reduction, upper and lower credible intervals (95% CI). Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand

Locations & seasons	Treatment	Median DR*	DR*: lower 95% credible interval	DR*: upper 95% credible interval
Indonesia wet season 2020	PFP 20	35	18	49
Indonesia wet season 2020	PFP 30	34	15	49
Indonesia wet season 2020	PFP 40	39	10	57
Southeast Asia 2021	PFP 20	28	17	37
Southeast Asia 2021	PFP 30	35	26	43
Southeast Asia 2021	PFP 40	39	30	47

*DR: damage reduction in PFP compared to CGP.

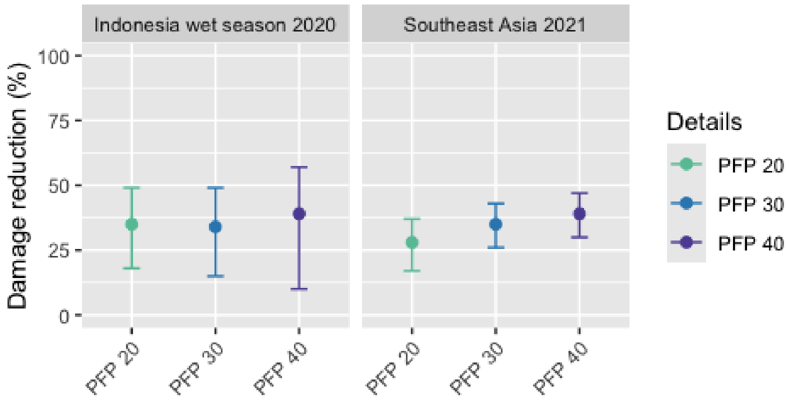

Figure 8. Overall damage reduction on the vegetative stages of maize (45 to 50 days after planting) due to mating disruption in pheromone treatment plots (PFP–pheromone foundational practice) at 20, 30, and 40 pheromone dispensers/ha compared to no-pheromone control plots (CGP–conventional growers practice). Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand.

plots. The PFP 20, 30, and 40 dispensers/ha treatments provided a median damage reduction of 28, 35, and 39%, respectively, compared to the control plots. PFP 40 treatment led to significantly greater damage reduction than PFP 20 treatment ($P < 0.05$; Bayesian P-value) (Table 3). However, the PFP 30 and 40 dispenser/ha treatments provided statistically equal damage reduction results.

Reduction in insecticide applications as a result of mating disruption

Insecticide applications in all PFP plots were based on the threshold for the highest treatment rate of PFP 40, while control plots were sprayed at the discretion of the participating farmers. The number of insecticide applications in the PFP versus control plots is displayed for each location in Figure 9. At all locations, the pheromone treatment plots always received fewer insecticide sprays. At least two applications were made in the control plots and as many as eight applications were made in the vegetative phases of the crop. None of the PFP plots received more than two insecticide sprays per season to control FAW at all 16 locations. Overall, insecticide applications were analyzed by a paired t-test, which showed that PFP fields used significantly fewer insecticide applications ($P < 0.001$; from paired t-test) (Figure 10).

Figure 9. The number of insecticide applications made to reduce FAW (fall armyworm, *Spodoptera frugiperda*) larval damage in pheromone treatment plots (PFP–pheromone foundational practice) compared to no-pheromone control plots (CGP–conventional growers practice) at various locations. Split by field size. Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand.

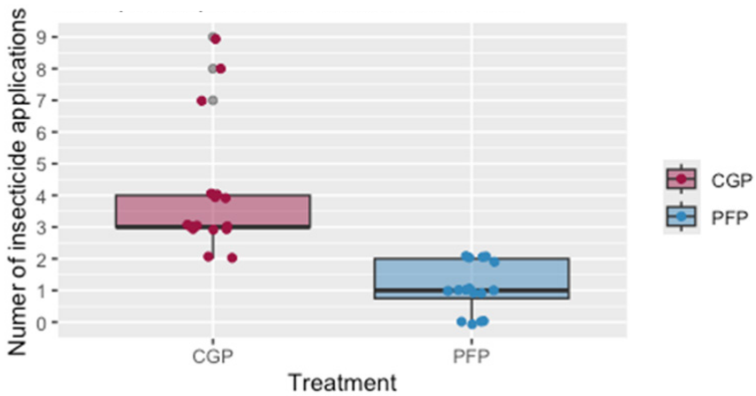

Figure 10. Insecticide applications made in pheromone treatment plots (PFP–pheromone foundational practice) compared to no-pheromone control plots (CGP–conventional growers practice). Each data point is the represents one trial location field. Sixteen locations: 2020 - Five locations are distributed in Java and Sumatra Islands in Indonesia during the wet season. 2021 - Seven locations are distributed in East Java (Indonesia) and four across Thailand.

DISCUSSION

Spodoptera frugiperda, the fall armyworm (FAW) its invasion in 2019, has become a significant threat to maize production in Southeast Asian maize-growing areas, including Indonesia and Thailand (Herlinda et al. 2022). Subsidized by the government, synthetic insecticides have become an emergency control strategy for FAW in invaded countries (Huesing et al. 2018). Insecticide applications are the only measures currently available to farmers for managing FAW. The present study shows the potential of mating disruption for the wider, safer, and more sustainable management of FAW in Indonesia and Thailand. These field studies were undertaken in 2020-21 in Indonesia and Thailand, where we tested LDPE dispensers filled with 2.5 grams of blended FAW sex-pheromone active ingredients, Z9-14Ac, and Z11-16Ac in a ratio of 87:13. These dispensers were installed in contiguous maize-producing areas of Indonesia and Thailand. At 16 locations, three different densities (20, 30, and 40 dispensers/ha) were tested in 9-ha plots for each treatment. MD for FAW requires larger areas to be treated, as FAW moths can fly long distances, and there is a possibility of already-mated females migrating into the pheromone-treated (PFP) plots (Cardé 2021).

Pheromone traps with FAW-specific pheromone lures to capture male moths in conventional farmer plots can be used to monitor the population level of FAW (Muthukumar & Kennedy 2021) and also as a base to measure trapping reduction when compared to the moth capture in PFP plots (Cork et al. 2008). Based on the number of male FAW moths captured in PFP treatments compared to CGP areas, we can see a dose response where a higher density of dispensers provided higher MD in Indonesia's wet season in 2020. The PFP 40 dispensers/ha treatment had the highest effect, with 88% median trap reduction. However, when we tested more locations in 2021, PFP 30 and 40 dispensers/ha rates had statistically equal performance of 90-93% median trapping reduction. The virulence of FAW populations differed from season to season and from location to location. Higher FAW moth captures in the control areas were observed in Thailand than in Indonesia. However, cropping patterns and practices have not been explicitly investigated in these studies. However, this suggests that the dispersal patterns of FAW largely depend on the monoculture of maize, as seen in Thailand and East Java locations, as compared to the more fragmented and intercropping patterns of maize production in Sumatra Island of Indonesia. The increased moth population in Indonesia from the 2020 wet season to the 2021 dry season may be caused by several factors, including a carry-over population from the previous season and rising temperatures suitable for FAW population growth (Maharani et al. 2021).

The trap reduction analysis results showed that PFP 40 dispensers/ha consistently performed in all five locations during the 2020 Indonesia wet season, and PFP 30 dispensers/ha provided statistically equal performance to PFP 40 in all 11 locations tested in Thailand and Indonesia, with a median season-long trapping reduction of 90%. The higher trapping reduction in the PFP treatment plots proves that MD prevents males from effectively finding female FAW moths via competitive sexual confusion (Miller & Gut 2015). The density of PFP 30 dispensers/ha pheromone dispensers resulted in higher pheromone concentrations in the air, causing sexual confusion and difficulty in finding a mate. The dispenser density effect can be seen in Indonesia and Thailand, where PFP with 30 dispensers/ha treatment led to significantly greater trapping reduction than PFP with 20 dispensers/ha.

In the absence of direct measures of mating disruption, such as those from mating tables or tethered female moths (McVeigh et al. 1983), a reduction in infestation by the insect pest is the only reliable indication that mating disruption has occurred (Cork et al. 1996). The damage caused by the larval population was assessed based on the severity of 0 to 9, as Davis et al. (1992) suggested. Compared to CGP, MD in PFP treatments significantly reduced larval damage, primarily due to lower mating and subsequent oviposition by female FAW moths. Mitchell & McLaughlin (1982) reported the effect of MD on FAW egg deposition reduction. The decreased FAW reproduction led to a 34–35% reduction in larval damage in the PFP 30 dispensers/ha treatment compared to the CGP. It is also probable that infestation levels underestimate mating disruption, presumably because some of the larvae in the PFP plots originated from immigrating gravid female moths. Ge et al. (2021), who worked on the reproduction and migratory flights of FAW female moths, estimated strong flight ability during the early oviposition phase. It is likely that in the presence of suitable oviposition sites, females lay their eggs as soon as possible after mating. Thus, in the trials described here using plots of 9 ha surrounded by maize of a similar age, immigration may not have been extensive.

In the case of FAW, direct yield losses can occur through larvae feeding on the developing or mature part of the harvested plant (e.g., invading the ears of maize and feeding on the cob or feeding directly on the grain), thereby directly reducing yields (Harrison 1984). Indirect yield losses can occur through defoliation, which can minimize grain production owing to a decrease in the photosynthetic area (Vilarinho et al. 2011) and/or the loss of seedlings. In the present study, all damage assessments were performed during the vegetative stages of maize, as these stages are vulnerable to FAW attacks. These are the stages of maize where insecticide applications are accessible, owing to the height and growth of the maize crop. Since no comparison with infestation levels in completely untreated plots was possible, insecticide applications were made in both PFP and CGP areas whenever the economic threshold level of 20% of the plants reached a Davis scale of three or above. With a low damage incidence in the PFP plots, frequent insecticide applications were not required compared with CGP areas. On average, the farmers participating in the PFP areas sprayed only once in the season compared to two to eight applications in CGP plots, thus reducing the economic and exposure challenges of insecticide applications.

CONCLUSION

An alternative, practical, and adaptable technology is needed to manage FAW and reduce the dependence on synthetic insecticides. Pheromone-mediated mating disruption is an alternative to insecticide application. Research conducted from these 16 locations across Indonesia and Thailand in multiple seasons supports the proposition that fields with mating disruption dispensers incurred lower FAW damage with fewer insecticide applications than current conventional practices. The results suggest that mating disruption offers farmers a more effective means of control than the current management practices. Pheromone-based insect pest management has zero residues and is nondetrimental to humans and the environment. This work in Indonesia and Thailand suggests that it is a sufficiently robust technology that can be extended to other countries to manage FAW.

ACKNOWLEDGEMENTS

We want to acknowledge the assistance provided by all Kelompok Tani grower groups in Indonesia and farmers in Thailand in granting access to their farms. Thanks to Prof. Dr. Ir. Purnomo, Dr. Ir. I Gede Swibawa, and Dr. Puji Lestari, University of Lampung, Sumatra, Indonesia, for their expert advice.

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