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Concerted action needed among smallholders when using mass trapping of insect pests

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ABSTRACT

Mass trapping with pheromones is an effective method for controlling insect pests. However, it is unknown whether this is effective for smallholders with typically fragmented holdings, as local depletion by traps may be (over)compensated by the attraction of male moths from surrounding fields. This was tested on a major pest in eggplant, the shoot and fruit borer moth (*Leucinodes orbonalis*). In a two-year field experiment in Bangladesh, moth catches and fruit infestation were compared across isolated fields with a grid of 4 (2 by 2) traps, 24 (4 by 6) traps (10 m distance between traps) and farmers' practice fields (fields without traps but with spraying). Additionally, in one year, three networks with respectively 22, 28, and 40 traps were installed in scattered but nearby fields to compare results to the 24–trap fields. Across each season, moth catch per trap per week was three times higher in the 4–trap fields than in the 24–trap fields or the networks. Fruit infestation was comparable between 4–trap fields and farmers' practice fields in both years, while fruit infestation in 24–trap fields was 25 percentage points lower, showing effective local depletion of male moths only occurred in 24–trap fields. Trapping with networks of 22 – 40 traps yielded comparable results to the 24 contiguous traps providing evidence that loosely organized networks of multiple traps could also be effective. Given their plots are generally much smaller than 2400 m^2, smallholders can only make trapping effective if they take concerted action.

1. Introduction

Pheromones are semio-chemicals that contribute to pest management by modifying insect behaviour in a range of ways (Howse et al., 2013). Pheromones, particularly sex pheromones, interfere with insect reproduction and thereby provide pest control (Klein and Lacey, 1999; Witzgall et al., 2010). When used as mass trapping, traps baited with synthetic sex pheromone lures are placed to remove a large proportion of male insects leading to lower egg deposition by females and thus provides long-term pest control (El-Sayed et al., 2006; Suckling et al., 2015). Control by mass trapping has shown considerable success for a wide range of insects, especially species of Lepidoptera, Coleoptera, and Diptera (El-Sayed et al., 2006; Baker, 2009; Witzgall et al., 2010). Pheromones are species-specific, highly selective, and non-toxic to mammals or beneficial insects including the natural enemy complex (Cardé and Millar, 2009; Witzgall et al., 2010). While insecticides cause resistance in pests, secondary pest outbreaks or pest resurgence, pheromones do not have these same problems (Witzgall et al., 2010; Blassioli-Moraes et al., 2019). To alleviate the risks of pesticide use, pheromone-based pest management has become a valuable tool in integrated pest management (IPM) (Witzgall et al., 2010).

For mass trapping to be effective, the density of traps should be high enough to effectively reduce the local male insect population (Riedl, 1980; Jamieson et al., 2008; Larraín et al., 2009). Moreover, the spatial arrangement of traps will influence how many males are caught in those traps. When traps are arranged in grids, the traps on corners are expected to catch more male insects than those in the centres because corner traps are likely to attract male insects from a larger area while they 'shield' the central traps from the immigrant moths. For the same reason, plants in solitary plots with just a few traps or plants in plots that

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are at the corner of an area with many traps will likely be more heavily infested than plants in plots located in the centres of the area with many traps. These issues are especially relevant in developing countries where farming takes place on fragmented holdings of small fields. Thereby, it is crucial to determine whether traps should form a continuous grid or whether they would be equally effective if placed in networks of a few nearby but slightly scattered fields.

Farmers in South and South-East Asia are typically smallholders with fragmented farmland, including in Bangladesh, where average plot size for smallholders of 800 m^2 was reported for 1996 (Ahsan et al., 1989; Jha et al., 2005; Niroula and Thapa, 2005; Rahman and Rahman, 2009). This is also true for eggplant (*Solanum melongena* L.) farmers in Bangladesh, and fragmentation has continued since. These farmers suffer from severe yield (30 − 90%) and economic losses due to infestation by the eggplant shoot and fruit borer moth (ESFB, *Leucinodes orbonalis*, Lepidoptera: Pyralidae) (Alam et al., 2006; Srinivasan, 2008; Nahar et al., 2020). To combat this pest, farmers weekly spray broad spectrum pesticides alone or in cocktails (Mohiuddin et al., 2009; Shelton et al., 2018; Nahar et al., 2020). Such intense applications of a range of insecticides have caused classic pesticide-use problems including insecticide resistance (Ruberson et al., 1998; Chowdhury et al., 2013; Miah et al., 2014). Moreover, pesticides are found ineffective and wasting farmers' money, while pheromone trapping in principle provides a good alternative for these farmers (Nahar et al., 2020). Indeed, two decades ago, a mass trapping treatment against ESFB was developed (Cork et al., 2001, 2003, 2005) and promoted in South and South-East Asia, including Bangladesh (Alam et al., 2006). The Department of Agricultural Extension, Bangladesh, has picked up this method and incorporated pheromone trapping as one of the components of eggplant IPM in their farmer field school IPM curricula (Mukta, 2020). However, neither the IPM developer nor the extension material provides an indication of how this mass trapping can best be implemented in small land holders' fields given the need for a sufficient trap density and proper trap arrangement to create a large enough depletion of males to arrive at lower mating success and egg deposition.

In a previous participatory ESFB management study with farmers Nahar et al. (2020) tested pheromone trapping alone and in combination with biorational insecticide applications by placing traps as a network across nearby scattered fields of varying size. They found the trapping to be effective, safe to natural enemies and economically sound (Nahar et al., 2020). Farmers considered that maintaining traps was easy and trapping was cost-effective compared with conventional spraying. However, the study did not test whether trapping remains effective when a farmer uses traps on a single small field in a landscape where the same crop is widely grown or whether adoption of this technique by multiple farmers is needed. Trapping in a single field might attract more male moths than are caught in the traps if the neighbouring fields are kept without traps. Farmers shared similar concerns that trapping as an individual might make the trapping effort futile, or even worsen their losses (Nahar et al., 2020).

This study aims to contribute to insight into how pheromone trapping of ESFB can be made effective for smallholder eggplant farmers. Across two seasons, a comparison was made between isolated single fields with 4 traps (2 × 2 traps) and 3 − 4 comparable fields allowing for a continuous grid of 24 traps (4 × 6 traps). Additionally, in one season, these results were compared to three networks of 22, 28 or 40 more distantly spaced traps, representing a more realistic situation of farmers whose fields are not positioned side by side. The following hypotheses were tested: 1) trapping in single small fields is ineffective because more male moths are attracted from neighbouring fields outweighing the local depletion. Therefore the number of moths caught per trap per week will be higher in the 4−trap setting than in the 24−trap setting, or the networks of 22 − 40 traps on scattered nearby fields; 2) as a consequence of the former, trapping with 4 traps in single fields is ineffective in terms of reducing fruit infestation and increasing yield; 3) when the trapped area is larger, either as continuous trap setting (24 traps) or as a network on scattered nearby fields, male moth depletion is effective, as evidenced by lower infestation and higher yields; 4) plants in the centre of the larger continuous trapped area is significantly better protected than plants at the corners of this area or in a network.

2. Materials and methods

2.1. Study site

The experiment was conducted in Pirijpur village (25°02′13"N, 89°50′08"E), Jamalpur district, the major eggplant growing area of Bangladesh, located in the so-called Old Brahmaputra floodplain. Farmers cultivate eggplants during the cool dry season (Rabi season: September–March) on plots of generally 400–600 m^2.

2.2. Trap settings

In two seasons, two types of trap settings were tested: a 4–trap setting (a single 400 m^2 field) in seven replicates in Year 1 (2016 − 2017) and three replicates in Year 2 (2019 − 2020), a 24–trap setting (in 3 − 4 adjacent small fields, 2400 m^2) in five replicates in Year 1 and three replicates in Year 2 (Fig. 1). Allocation of fields over the landscape was based on distance requirements outlined below and farmers' willingness to contribute fields for this study. For comparison of fruit infestations without pheromone trapping, there were nine and three replicates of observation plots in farmers' practice fields in Year 1 and Year 2, respectively. Distances between all treatment plots (farmers' practice fields, 24–trap fields, and 4–trap fields, and their replicates) were kept at a minimum of 100 m.

In Year 1, a set-up with three replicates of a network of traps around scattered nearby fields was also tested (Fig. S1 in Supplementary material). The three networks were considered replicates that had respectively 22, 28 and 40 traps, spread over 3–5 fields with between 4 and 12 traps per field and a between-field distance of 10 − 25 m within networks, while the distance between nearest traps of adjacent replicates of the networks was 44 and 50 m (Fig. S1). This distance is larger than a reported estimate for the plume size of comparable traps (20 – 40 m; Onufrieva et al., 2020).

Farmers establish eggplant fields through transplanting of nursery-grown seedlings. Traps were installed 30 − 45 days after this transplanting in a 10 m × 10 m grid keeping 5 m distance from all field borders. Water pan traps (Ispahani Biotech, Bangladesh) were mounted on bamboo poles and baited with lures consisting of a polyethylene vial impregnated with 3 mg of a (97% W/W) (*E*)-11-hexadecenyl acetate (E11–16:Ac) and (*E*)-11-hexadecen-1-ol (E11–16:OH) blend dissolved in 0.1 ml hexane solution (Ispahani Biotech, Bangladesh) (Fig. 2). Traps were provided with detergent mixed with water for effective drowning of trapped moths. Trap height was adjusted periodically according to plant growth to keep it 10 cm above the canopy. Lures were replaced every four weeks; water with detergent was changed weekly. In the 24–trap fields, traps were placed in 4 lines of 6 traps. According to this setting, there were 4 corner-, 12 border- and 8 centre traps (Fig. 1b). In

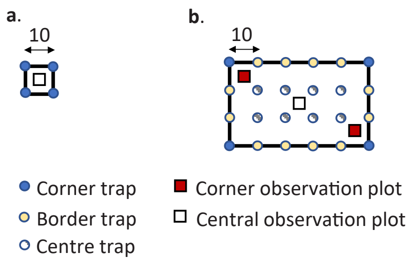

Fig. 1. **(a)** A 4-trap setting with its central observation plot. **(b)** A 24-trap setting, with two corner observation plots in opposite corners and one central observation plot. Size of all observation plots was 4 m × 4 m.

Fig. 2. Pheromone traps in the field. As the crop was growing the traps could be fixed higher along the stick to keep them above the canopy. The small pending plastic vial visible in the triangular opening in the bucket contains the pheromone lure which was replaced every 4 weeks. At the bottom of the trap the greenish colour indicates the water with soap in which the moths drowned when caught in the trap.

the 4–trap fields, all traps were in corners (Fig. 1a). In the networks of fields, the 4 − 12 traps per field were always installed in two lines thus having four corner traps, a varying number of border traps and no centre traps (Fig. S1). No spraying was done in pheromone trap treated fields; farmers were promised monetary compensation in case yield was compromised. In the control plots on farmers' fields, farmers applied the insecticides Chlorpyrifos (48 EC), Cypermethrin (10 EC), Malathion (57 EC) alone or in cocktails weekly at a concentration of each 1.5 ml/L of water (760 ml/ha) from 20 days after transplanting to the end of the season.

2.3. *Observations*

Moths per trap were recorded weekly while replacing the water in the traps. When trapped moths were few, all moths were hand-picked directly by forceps, counted, and discarded. When there were many moths, water from the trap was poured on muslin cloth, and moths were counted.

Eggplants were harvested weekly from 4 m × 4 m observation plots (49 plants) of 24–trap, 4–trap of network fields (Fig. 1 and Fig. S1), and farmers' practice fields. To avoid influence of spraying in nearby fields, observation plots were placed in the centre of fields with a minimum of 5 − 8 m distance from borders of nearby fields for 4–trap fields and the networks. In the 24–trap fields, eggplants were harvested from three observation plots: two diagonally placed corner plots and one plot in the centre (Fig. 1b). To avoid interference by pesticide applications, corner observation plots were at least 8 m away from the borders of any nearest field. Healthy and infested eggplants were weighed using a digital scale. Any fruits having holes, frass attached or a secondary infection were considered infested. The percent infested fruits per plot was both calculated per observation day and cumulatively over the season; the latter was calculated based on cumulative weight (kg) of infested and healthy fruits. Some plants were lost due to bacterial wilt; however, insect damage and wilt losses were found unrelated (Nahar et al., 2020). Therefore and to keep the number of sampled plants equal, any plant lost in an observation plot due to bacterial wilt was compensated by including a plant from the rows directly bordering the observation plot. Thereby, a total yield was obtained as if there were no wilt losses.

2.4. *Statistical analyses*

Data were tested for normality and homogeneity of variances using Shapiro-Wilkinson and Levene's tests. Yield data met all assumptions and were analysed using a standard analysis of variance with post-hoc mean separation using Tukey's HSD test ($\alpha = 0.05$). Moth count and fruit infestation data were not normally distributed, representing count data, and were therefore analysed with models using negative-binomial error distributions (Zuur et al., 2009). A beta distribution was used for fruit infestation to account for the fact that the infestation was bounded between 0 and 1 (Douma and Weedon, 2019). Given the hierarchical design of the data (multiple measurements per trap and multiple traps per field), data were analysed using mixed effect models using the aforementioned error distributions. Random effects were added to correct for possible correlations between observations coming from the same field or trap. As fixed effects observation time, treatment and their interaction were tested. For computational reasons the two years were analysed separately. All main effects in the models were tested with type III Wald tests. Post-hoc comparisons were tested with Tukey's HSD test. All statistical analyses were performed in R version 3.6.1 (R Core Team, 2022) and the packages car (Fox and Weisberg, 2019), emmeans (Lenth, 2023) and glmmTMB (Brooks et al., 2017).

3. Results

Despite clear infestation differences between years in farmers' fields (Fig. 3b) and in trap catches across treatments (Fig. 3a) qualitative differences in treatment effects on both trap catches, fruit infestation and yields were very similar (Figs. 3 and 4).

3.1. *Trap catches*

Trap catches were highest in the 4–trap fields as was the seasonal average catch per trap per week (Figs. 3a and 4a, 4b) and roughly twice that in corner traps of the 24–trap fields (for the 4–trap fields 44.8±5.5 and 22.7±2.8 moths per trap per week for Year 1 and Year 2, respectively, and for corner traps of 24–trap fields 24.2±3.0 and 13.8±2.1 moths per trap per week for Year 1 and Year 2, respectively), and three times that in traps in networks (14.8±1.9 moths per trap per week in Year 1 only). Within the 24–trap, the corner traps caught the most, followed by the border traps and the centre traps. The patterns described above were remarkably consistent across the two years. As the interaction between time of observation and treatment was significant (Year 1, X^2 1065, d.f.=80, p-value $<$ 2.2e-16; Year 2, X^2 132, d.f.=21, p-value $<$ 2.2e-16; details in Table S1 in Supplementary material) the statistics of the differences between treatment effects per observation day, including the network for Year 1 are reported (details in Table S2 in Supplementary material).

Averaged across the season, the number of male moths caught in the centre (8.2±1.0 and 5.5±0.9 moths per trap per week for Year 1 and Year 2, respectively) and border traps (16.5±2.3 and 8.0±1.5 moths per trap per week for Year 1 and Year 2, respectively) of the 24–trap fields were significantly lower compared to the number of moths caught in the 4–trap fields; only for the first two observation days in Year 2 catches were similar (Figs. 3a, 4a, 4b and Table S2). Likewise, the trap catches in the corner traps of the 24–trap field were always numerically lower than the catches in the 4–trap fields, except at the first observation days in Year 2. In Year 1, in 6 out of 21 observation days and in Year 2, in 11 out

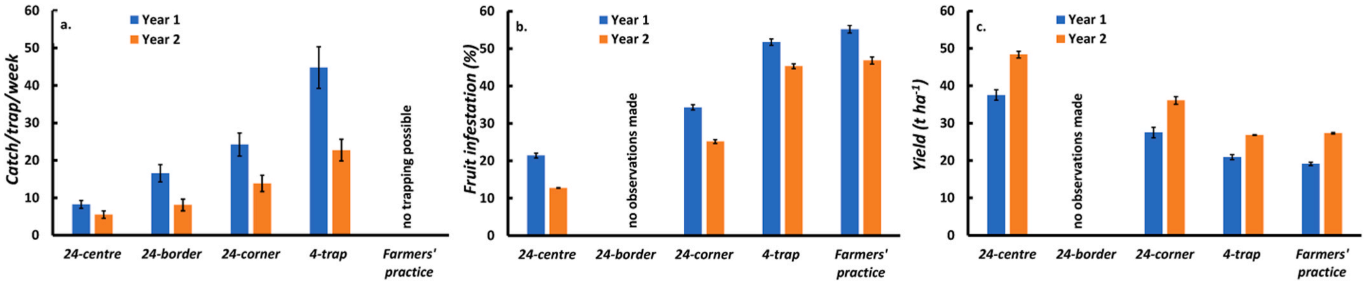

Fig. 3. **(a)** Seasonal average of number of eggplant shoot and fruit borer (ESFB) male moths caught per trap per week, **(b)** Percent fruit infestation by ESFB caterpillars in the cumulated fruit harvest, **(c)** Estimated eggplant yield (t ha^{-1}) under different trap settings and farmers' practice. In Pane 'a' data for farmers' practice plots are absent as by design no traps were installed there, in Panes 'b' and 'c' data for 24-border are absent as no observation plots were installed there. Error bars represent standard errors of the mean.

of 21 observation days these differences were not significant. The catches in the centre traps of the 24–trap field were always lowest, except for two observation days in Year 2 and on 3 of the 21 observation days in Year 1 and on 12 of the 21 observation days in Year 2 when catches were not significantly different from the border traps. Catches in the border traps were always numerically lower than in the corner traps, although on more than half of the observation days (13 out of 21 observation days in Year 1, 10 out of 21 observation days in Year 2) catches of corner and border traps were not significantly different (Table S2).

Corner and border traps of 24–trap field and traps in networks were not systematically catching different numbers of moths in Year 1, although on half of the observation days catches were found to differ significantly. When significantly different, corner traps always had higher catches, while traps in networks and border traps took turns in having the next higher catches (Figs. 4a, 4b, Fig. S3a and Table S1).

3.2. *Fruit infestation*

The fruit infestation in the cumulated fruit harvest between farmers' practice fields and the 4–trap fields were very comparable, 55% and 52% infestation respectively for Year 1 and 47% and 45% respectively for Year 2 (Figs. 3b and 4c, 4d). As the interaction between time of observation and treatment was significant (Year 1, $X^2 = 523$, d.f. = 60, p-value <2.2e-16; Year 2 $X^2 = 814$, d.f. = 57, p-value < 2.2e-16, Table S3) in both years of the study, treatments are compared per observation day. At most dates across the seasons (11 out of 16 observation days in Year 1 and 19 out of 20 observation days in Year 2), infestations of farmers' practice fields and 4–trap fields were not significantly different (Table S4). When it deviated in Year 1, the 4–trap fields had significantly lower infestation than farmers' practice fields, suggesting a minor effect of the pheromone traps (Table S4). This minor effect of the pheromone trapping could not be observed in Year 2 as there was only one observation day at which the farmers' practice fields and the 4–trap fields differed significantly.

The fruit infestation over time in the 4–trap fields and the farmers' practice fields showed a marked difference compared to the 24−trap fields. In the 4–trap and farmers' practice fields, fruit infestation was increasing over time, while in the 24−trap field infestation remained more or less stable or decreased over time (centre traps). Across the season, the fruit infestation in the 4–trap field was always higher than the fruit infestation in the corner and centre plots of the 24–trap fields in Year 1, although in 1 out 16 observation days this difference was not significant for the centre plots, and in 4 out of 16 dates this difference was not significant for the corner plots. In Year 2, only on 60 days after transplanting the 4–trap fields had a lower fruit infestation and in 18 out

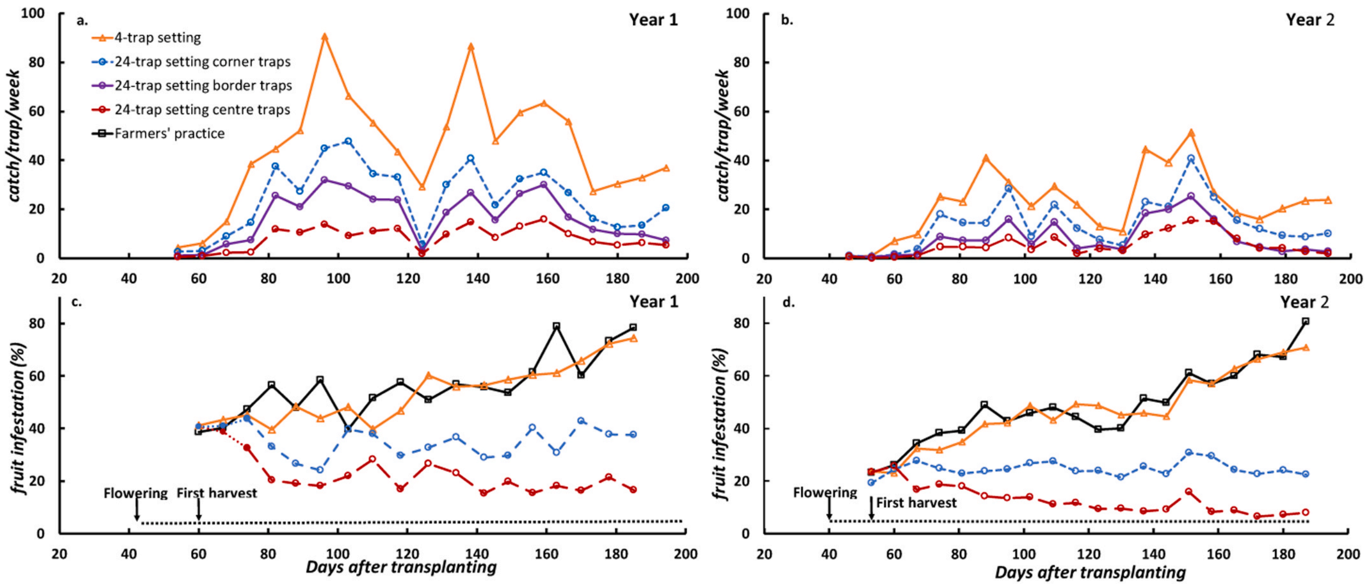

Fig. 4. **(a, b)** Weekly eggplant shoot and fruit borer male moth catch over time in different trap settings for Year 1 (a) and Year 2 (b); by design there were no traps installed in farmers' practice fields. **(c, d)** Percent fruit infestation over time under different trap settings and in farmers' practice fields for Year 1 (c) and Year 2 (d). The dotted lines and filled symbols for infestation in Pane 'c' observed in the 4-traps and 24-traps fields indicate data obtained before effects could be expected based on late placement of traps (Section 2.2). Dotted horizontal lines at the bottom of Panes 'c' and 'd' indicate the duration of pheromone trapping.

of 20 dates the infestation was lower in the centre plots and in 16 out of 20 dates in the corner plots. Infestation of centre plots of 24–trap fields was always numerically lower than that of the corner plots of the same trap setting from 67 days after transplanting onwards; only on 6 out of 16 observation days in Year 1 and 5 out of 20 observation dates in Year 2 differences were not significant. This happened mainly at the beginning of the harvesting period (Table S4).

Fields in networks in Year 1 showed lower infestation than centre plots of 24–trap fields at the beginning of the harvest period probably because traps in these networks were installed 15 days earlier than in 24–trap fields (Fig. S3b); however, from 118 days after transplanting onwards centre plots gradually showed lower infestation than fields in networks (in 4 out of 10 dates this difference was not significant, Fig. S3b and Table S4). Consequently, the cumulated weekly harvested fruits for the centre plots of the 24–trap fields showed substantially lower infestation (11–13 percentage points) than for observation plots in the corner of the 24–trap fields and fields in networks, and all three had significantly lower infestation than plots exposed to farmers' practice (Figs. 3b, S2b). Corner plots of 24–trap fields and fields in networks showed a similar infestation throughout the season except at the beginning of the harvest period when infestation in networks was lower due to the mentioned time difference in trap installation dates between these fields (Fig. S3b).

3.3. Yield

Significantly higher fruit yields were obtained from centre and corner plots of the 24–trap fields than from plots of the 4–trap fields and farmers' practice fields (Fig. 3c). Plots in networks also showed higher yield than 4–trap field plots (Fig. S2c). Farmers' practice and 4–trap field plots produced similar yields (19 – 20 t/ha for Year 1 and 26 – 27 t/ha for Year 2), while an extra 7 – 8 t/ha (Year 1) and 9 – 10 t/ha (Year 2) was obtained in the corner plots of the 24–trap fields; finally, centre plots of the 24–trap fields yielded yet another 10 t/ha (Year 1) and 12 t/ha (Year 2) more so almost double the yields of plots in farmers' practice fields (Fig. 3c). Fields in networks obtained 10 – 11 t/ha more compared to 4–trap and farmers' practice fields, so roughly as much as corner plots in the same year (Year 1) (Fig. S2c).

4. Discussion

The aim of the study was to test whether pheromone traps can be employed effectively to reduce fruit infestation by ESFB on single fields of smallholder farmers when surrounded by fields with the same crop, or whether concerted action of neighbouring farmers, or nearby – but not necessarily neighbouring farmers in a network setting is needed. Putting traps in a single small field (400 m^2 with 4 traps) was ineffective because it showed similar infestation as farmers' conventional practice fields without trapping for most of the observation days (Figs. 4c and 4d). Despite catching on average three times more moths per trap per week than traps in 24–trap fields or networks, 4–trap fields showed 19 – 32 percentage points higher fruit infestation than the two previously mentioned trap settings (Figs. 3a, 3b and Figs. S2a, S2b). This finding strongly suggests that the attraction range of the traps is larger than the average plot size and this led to a net influx of male moths in the fields with the four traps installed. When the trap number and trapping area were increased to 24–trap fields in 2400 m^2 or to the networks of traps on nearby scattered fields (Fig. 1b and Fig. S1), local depletion was achieved (i.e. local trapping outweighed the attraction from surroundings) as evidenced both by the lower catches in the centre traps compared to the corners, as well as by the lower fruit infestation in the centre plots compared to the corner plots within the 24 traps and the overall lower fruit infestation in the plots of 24–trap fields and networks compared to the 4–trap fields and farmers' practice fields. It suggests that if trapping is done in a continuous grid over a larger area (Fig. 1b), plots in the central part of that area will be more protected and plots in corner areas will have the same protection as the fields in the more scattered sets of traps in a network setting of traps (Fig. S1). These findings have important practical implications for the introduction of mass trapping in the context of smallholder farming communities (see "Management implications").

4.1. Possible reasons for differences in efficacy of mass trapping between 4–trap and 24–trap fields

Mass trapping aims at locally depleting male populations to such an extent that it impairs the mating success and thus reduces infestation (El-Sayed et al., 2006). On average across the season, traps from 4–trap fields attracted around thrice as many male moths per trap as traps in the 24–trap or network setting fields (Figs. 3a and 4a, 4b). Despite the observed mass trapping in the 4–trap fields of around 23–45 moths per trap per week (Fig. 3a), fruit infestation was very comparable to plots where no traps were placed (farmers' practice fields) and substantially higher than in the observation plots in 24–trap fields and networks (Figs. 3b and S2b). It is to be noted that the farmers' practice included weekly spraying but that this was found not to reduce infestation (Nahar et al., 2020). The lower numbers of trapped male moths in the 24–trap fields (8–15 moths per trap per week) were accompanied by lower infestation in both corner and centre observation plots (Fig. 3b). Assuming that the female distribution and egg deposition are not influenced by the pheromone traps, females will be equally available across the landscape to mate with any males that are not (or not yet) caught. Male moths may become the limiting factor of the reproductive success of females if the male population is sufficiently depleted locally. Considering that the change in percent infestation over the season reflects effective female egg laying the data demonstrate that egg deposition was indeed lower with mass trapping of male moths in the 24–trap fields but not in the 4–trap fields. Hence, more than four traps need to be installed for effective moth control.

Compared with the centre plots and traps, the corner plots and traps of the 24–trap fields showed higher fruit infestation (13 percentage points higher; Fig. 3b) and higher moth catches (Fig. 3a). Due to its location in the corner, attraction from surroundings probably partially compensated the local male population depletion. Despite this attraction from surroundings, depletion in corner plots was still more effective than in 4–trap fields as indicated by the 17 – 20 percentage points lower fruit infestation and roughly half the number of male moths caught per trap per week. One of the reasons for this higher effectiveness might be that the male moths attracted by the lures in the 24–trap setting were spread over more traps and a larger area. So, dilution of attracted moths is larger when more traps are situated close-by. A similar type of catch difference between corner and centre traps was reported in other studies for Lepidopteran and Dipteran insects (Mafra-Neto et al., 1988; Mafra-Neto and Habib, 1996; Suckling et al., 2015). Lower infestation in networks might also be linked to the fact that attracted moths were diluted over the larger area.

Infestation was equally reduced in the corner plots of 24–trap fields and networks and infestation in centre plots was either comparable or lower than both, the latter especially towards the end of the season (Figs. 4c, 4d and S3b). This means that organizing traps in networks led to sufficient depletion of the male moth number to have a net reduction of female egg deposition to levels comparable to those of the corner plots of the 24-trap fields. Although fields in the networks sometimes had four traps like the individual plots in the 4–trap fields (Fig. S1), adjacent plots in these networks were located sufficiently close-by to dilute the moth numbers. Future studies should identify the maximum distance possible between traps while maintaining a reduction in fruit infestation.

4.2. Population build-up and infestation over time

Pheromone trapping led to important changes in population dynamics over time. In the 4–trap fields, plausibly due to attraction from surroundings, the male moth population remained higher throughout the season particularly from 60 days after transplanting onwards compared with the 24–trap and network fields (Figs. 4a, 4b and S3a), and fruit infestation gradually increased (Figs. 4c, 4d and S3b). Especially from 126 days after transplanting to the end of the season infestation drastically rose as was observed in farmers' practice fields for Year 1 and from the beginning to the end of the season for Year 2 (Figs. 4c, 4d). The completion of the life cycle of ESFB has been reported to take 25 – 40 days (Srinivasan, 2009; Mainali, 2014; Mannan et al., 2015). The first moths were observed around 30 days after transplanting. After roughly three generations (100 – 126 days after transplanting), the infestation went up gradually and prominently in the 4–trap fields and under farmers' practice (Figs. 4c, 4d). In the corner and centre plots of the 24–trap fields and in the network fields, infestation was stable throughout the season and lower than in farmers' practice fields at most observation days. However, only from half-way the season onwards a substantial reduction of infestation became apparent as populations did not get out of hand the way they did on farmers' practice fields (Figs. 4c, 4d and S3b). This effect was even more pronounced in the second year.

The infestation data at the start of the season in both years clearly show that there is a time lag of roughly one generation (25 – 40 days) (Srinivasan, 2009; Mainali, 2014; Mannan et al., 2015) between installing traps around flowering (40 – 45 days after transplanting) and reduction of infestation around 70 days after transplanting (Figs. 4c, 4d). This effect also shows in network fields, where the traps were installed 30 days after transplanting. Infestation in the network fields was lower than in farmers' practice fields at first harvest 60 days after transplanting (Fig. S3b). So, it takes time before trapping leads to effective population reduction.

Therefore, it can be concluded that: i) starting trapping early is essential for farmers, also as prices of eggplant fruits tend to be highest early in the season; ii) farmers have to wait quite a long time to see substantial reduction of infestation compared with their current practice; iii) farmers need to understand that there is a 20 – 30 day time difference between peaks in catches and peaks in infestation. The latter two aspects are important complications to scale out trapping among farmers. The data also tell how difficult it is to make farmers understand the efficacy of mass trapping because at the beginning of the season the effects are limited as shown by the small differences compared with farmers' practice (Figs. 4c, 4d).

4.3. *Management implications*

This study was conducted in a typical eggplant growing village of Bangladesh where approximately 80% of total cultivable land is occupied by eggplant (personal observation) and where fruit infestation by ESFB is around 50% (Nahar et al., 2020). Therefore, the question was how suitable pheromone trapping is when the average field of a single smallholder allows to install just four traps. Based on trap catches, infestation and yield, results from the present study indicate that such trapping indeed would not be profitable and in fact economically risky, supporting the intuition of farmers who stated, "if we put traps alone then we might attract more insects" (Nahar et al., 2020). However, when traps were placed in a larger grid of 4 × 6 traps or in networks of 22 – 40 more scattered traps on nearby fields, yield increased to a level that outperformed current farmers' practice as infestation was reduced by 23 – 25 percentage points compared to farmers' practice and the centre plots even reached 12 – 21% infestation, a reduction of 34 percentage points compared with farmers' practice, making it a very effective strategy compared to farmers' practice. Full control was not reached, as has also been reported in other successful cases of pheromone trap use; e.g., Cork et al. (2005) working on eggplants too reported a remaining 18% infestation. However, a lower infestation was observed in the second year of this study suggesting that trapping effects over a longer time frame may give even better results.

Given current field sizes and prevalence of eggplant cultivation in the study area, farmers of nearby fields should organise themselves. Although an exact minimum number of traps cannot be established from the current data, farmers should be informed to either organise themselves as direct neighbours to form a continuous 10 m × 10 m grid of 24 or more traps or create a network of at least 22 traps on nearby fields covering roughly 0.4 ha as in our networks. In a previous study over two years on ESFB management, trapping in the networks was found cost-effective (Nahar et al., 2020), therefore, trapping by installing a continuous grid of 24 traps would also be cost-effective. Installing 24 traps would require 3 – 4 farmers to organise themselves while sharing the costs and labour. The better control observed in the centre plots of the 24–trap fields indicates that more dense networks or larger fields will likely be more effective as the central area would become larger. Whether the centre of a larger area with a larger number of traps would be showing yet lower infestation than the centre of the 24–trap fields cannot be concluded without further research. However, other studies reported that increasing trapped area and thus trap number reduced infestation of caterpillars and bugs in various crops (Jamieson et al., 2008; Larraín et al., 2009; Sarfo et al., 2018). The observation that farmers who own the central plots will benefit more than those who are in the corners may potentially become a source of dispute. Such a dispute may also arise in a network setting as the farmers of the fields in the network that have no traps installed will be free riders that have the benefits of trapping, but not the costs of it. Hence, mass trapping for smallholders not only requires organisation of traps but also requires organisation among farmers.

5. Conclusion

This study is the first to show that mass trapping of ESFB in eggplant cropping is ineffective for an individual smallholder farmer, given the typical land holding size and high density of eggplant cultivation in a large part of South and South-East Asian vegetable production areas. When 24 traps were employed covering multiple neighbouring fields, local depletion of the population of male moths became larger than any attraction from surrounding areas giving an effective control. Thereby, concerted action of smallholder farmers is needed to make mass trapping successful. The data further seem to indicate that a continuous grid of 24 traps or a network of 22–40 traps on scattered but nearby small fields were equally effective arrangements. The networks maintained a minimum trap density of 1 trap per 200 m^2.

Further research could establish more exactly the minimum network size and trap density to suppress moth populations. Given the importance of the role of attraction in annihilating the targeted local depletion in mass trapping, establishing the exact attraction range of trap settings is needed to refine advice on trap density across environments that differ in moth density, the size of the fields, and the proportion of hosts in the landscape and thereby the minimum number of farmers that need to cooperate.

Extension services and research organisations in countries where smallholder farming is common should consider the above findings when recommending pheromone trap-based insect management to smallholders.

CRediT authorship contribution statement

Tjeerd-jan Stomph: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Jacob C. Douma:** Formal analysis, Writing – review & editing. **Naznin Nahar:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Peter De Jong:** Supervision, Writing – review & editing. **Mohammad Mahir Uddin:** Supervision. **Paul C. Struik:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: NAZNIN NAHAR reports financial support was provided by The Dutch Organization for Internationalization in Education. All other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109003.

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