Push-pull strategy combined with net houses for controlling cowpea insect pests and enhancing crop yields

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Abstract

Net houses can be used in tropical environments to protect crops such as cowpea against large insect pests, thereby avoiding pesticide treatments while sustainably mitigating the effects of climate change. We investigated a push-pull strategy to prevent small insect pest outbreaks in a net house. The push component consisted of two stimulus plants, i.e. *Cymbopogon citratus* and *Tagetes minuta*, and the pull stimuli consisted of visual cues from blue and yellow sticky traps. Field experiments were set up in central Kenya and conducted during a rainy and a dry season, involving an open field control treatment, and three management treatments consisting of (1) an open field push-pull treatment, (2) a net house treatment and (3) a combined net house + push-pull treatment. *Trialeurodes vaporariorum* infestations were lower in the net house and net house + push-pull treatments than in the two open field treatments during the dry period or in the control treatment during the rainy period. *Aphis craccivora* infestations were higher in the net house and net house + push-pull treatments than in the control and open field push-pull treatments during the dry period, while no differences were observed among treatments during the rainy period. *Megalurothrips sjostedti* infestations did not vary among treatments in both periods. Among the larger insect pests, *Clavigralla tomentosicollis* infestations were lower in the net house and net house + push-pull treatments than in the open field treatments during the dry period, while *Maruca vitrata* infestations were lower in the net house treatment than in the control. During the rainy period, *C. tomentosicollis* infestations were higher in the net house + push-pull treatment than in the net house treatment, whereas *M. vitrata* infestations did not vary among treatments. Compared to the control, *Empoasca* sp. infestations were lower in the net house and net house + push-pull treatments in both periods, and in the open field push-pull treatment in the rainy period. Cowpea pod and grain yield and quality were higher in the net house and net house + push-pull treatments than in the control irrespective of the period. Although the treatments 1 reduced some of the pests, the net house and net house + push-pull treatments were effective in protecting cowpeas against most of the pests while improving pod yields in both periods.

Keywords: Net house, integrated pest management, push-pull, sticky traps, insect pests

1. Introduction

Population growth in developing countries has increased the demand for safe nutritional food (Alexandratos and Bruinsma, 2012). Vegetable production plays an important role in feeding the growing urban population in sub-Saharan regions (OECD and FAO, 2016). Farmers have been resorting to intensive chemical pesticide treatments to reduce crop pest damage and thus help meet the rising food demand (de Bon et al., 2014). Chemical pesticides are effective for pest control but they often have concomitant negative impacts on beneficial arthropods, the environment and human health (de Bon et al., 2014). Netting technology provides an alternative for reducing chemical pesticide treatments (Martin et al., 2006, 2015) by protecting different vegetable crops against a wide range of pests, boosting soil moisture, stabilizing the air temperature and increasing crop yields and quality (Martin et al., 2006; Gogo et al., 2012; Saidi et al., 2013; Simon et al., 2014; Gogo et al., 2014b; Nordey et al., 2017). Knitted nets with a 30-40 mesh size (0.9-0.4 mm diameter) have proven effective as a barrier against large size insect pests (body length > 2 mm) such as lepidopterans and dipterans, while providing enough ventilation to mitigate the adverse climate conditions that prevail particularly in the Kenyan highlands (Martin et al., 2015). However, net houses with such netting do not provide an effective barrier to small insects (body length < 2 mm) as they can pass through the mesh.

We investigated a push-pull crop protection strategy based on insect cues combined with the use of netting technology to curb outbreaks of small insect pests in net houses. In the push-pull strategy, attractant and repellent stimuli from different sources are simultaneously used to control the spatial distribution of insect pests and thus reduce their abundance on the target crop (Cook et al., 2006). Attractant stimuli divert insects from the target crop by means of taste, egg-laying stimulants, volatile plant attractants, sexual pheromones, and visual stimulants. Repellent stimuli prevent insect pests from finding or accepting its host via the emission of repellent volatiles, alarm pheromones, anti-feeding agents, visual distractions, egg-laying repellents and irritants (Cook et al., 2006; Eigenbrode et al., 2016).

Cowpea, (*Vigna unguiculata* L. Walp) is an African indigenous vegetable (AIV) that can reduce food insecurity and malnutrition in Africa (Muniu, 2017) since about 200 million people consume cowpea grains or leaves (Popelka et al., 2006). For example, cowpea is the top ranking AIV cropped in Kenya, with a total of 65 million t produced over a 24,431 ha area (HCDA, 2014). Netting technology and the push-pull strategy could be combined to provide an

alternative solution for controlling large and small insect pests of cowpea, thus reducing the need for pesticide treatments.

The pod borer (*Maruca vitrata* Fabricius) (Lepidoptera: Crambidae), and the pod bug (*Clavigralla tomentosicollis* Stäl) (Hemiptera: Coreidae), are two large insect pests of cowpea that can cause 80% yield losses if no pesticides are applied (Ekesi et al., 2002; OECD, 2015). *C. tomentosicollis* feeds extensively on fresh pods (Koona et al., 2002), whereas *M. vitrata* feeds on both flowers and pods (Singh and Jackai, 1988). The bean flower thrips (*Megalurothrips sjostedti* Trybom) (Thysanoptera: Thripidae), and the black legume aphid (*Aphis craccivora* Koch) (Homoptera: Aphididae), are two small insect pests of cowpea that cause yield losses of 20–100%, depending on the outbreak severity (Ekesi et al., 1999; Obopile, 2006; Abtew et al., 2016; Mweke et al., 2018). The feeding activity of *M. sjostedti* larvae and adults can lead to flower abortion and shedding, thereby resulting in reduced crop yields, while heavy *A. craccivora* infestations may cause plant stunting and delayed flowering (Obopile and Ositile, 2010; Moritz et al., 2013). In addition, *A. craccivora* may transmit viruses to plants (Stoetzel and Miller, 2001; Borowiak-Sobkowiak et al., 2017). A previous study showed that *M. sjostedti* is attracted by blue colours (Muvea et al., 2014), while *A. craccivora* is attracted to yellow sticky traps (Webb et al., 1994)—we thus used sticky traps as a pull stimulus in our study. Our previous experiment using olfactory tests showed that Mexican marigold (*Tagetes minuta* L.), and lemongrass (*Cymbopogon citratus* DC. Stapf), plants in the vegetative stage were repellent to female *M. sjostedti* (Diabate et al., 2019a). Freshly cut lemongrass leaves produce citral, an organic volatile which is repellent to *M. sjostedti*. Mexican marigold and lemongrass are either repellent or insecticidal to *A. craccivora* (Morallo-Rejesus and Decena, 1982; Ofuya and Okuku, 1994). In this study, we combined these repellent push plants with the use of a net house. Insect control using a push-pull strategy can avoid the need for chemical insecticides, thereby increasing the opportunity of natural enemies to reduce insect pest populations (Khan et al., 1997).

We hypothesised that nets could effectively protect cowpea crops against large insect pests but not small insect pests. The aim of the present study was to evaluate the effectiveness of three control strategies against cowpea pests, by combining (a) use of an insect net house to provide a physical barrier, (b) repellent companion plants to provide an olfactory barrier, and (c) a visual trap in the form of coloured sticky strips as a pest attractant to increase cowpea grain yields and quality.

2. Materials and Methods

2.1. Site

The field trial was conducted at Kenya Agricultural and Livestock Research Organization (KALRO), Industrial Crops Research Centre (ICRC) Mwea (0°37'09.0"S 37°22'09.4"E) in Kirinyaga County, central Kenya. Mwea is one of the main areas in Kenya where vegetables, including cowpea, are grown (Musebe et al., 2005). The four seasons in Kenya include a short rainy season (October-November), a hot dry season (January-March), a long rainy season (March-June), and a cold dry season (July-August) (Hassan, 1998; Foba et al., 2015). The experiment was conducted during two periods: in the dry period from 3 October 2017 to 16 January 2018, and in the rainy period from 30 January 2018 to 22 May 2018. The dry period included one rainy month (10 October to 7 November 2017) and three dry months (14 November to 9 January 2018), with 358.8 mm total rainfall and 22.71°C mean temperature. The rainy period included one dry month (30 January 2018 to 27 February 2018) followed by three rainy months (27 February to 15 May 2018), with 679.5 mm total rainfall and 22.50°C mean temperature. Rainfall and temperature data were collected at the KALRO ICRC Mwea Kirogo Research Farm.

2.2. Treatments and experimental design

The net house was a locally manufactured high iron framed tunnel covered with a transparent knitted polyethylene AgroNet 0.4 (A to Z Textile Mills, Arusha, Tanzania) with a 40 mesh size (0.4 mm diameter hole size). The high tunnel was 5 m wide, 10 m long and 2.5 m high (flat on top) in the middle and 2 m high at the sides with a double door. Rain drops seeped through the top of the net house. Coloured (blue, yellow) sticky traps were purchased from the RealIPM Company, Thika, Kenya. Cowpea, *V. unguiculata* var. Machakos 66 (M66), seeds were purchased from Dryland Seed Ltd., and lemongrass seedlings were from Simlaw Seeds Company Ltd., in Nairobi, Kenya. Mexican marigold seeds were field collected at KALRO-ICRC Mwea. About 40 kg of cow manure was spread per plot (10 m × 5 m) 2 weeks before sowing the cowpea seeds. Two cowpea seeds were sown in two hills on each side of the micro-irrigation emitters at a distance of 25 cm with 1 m inter-row spacing. Each experimental plot measured 5 m × 10 m and 60 cowpea plants were planted per row, for a total of 300 plants (60 plants × 5 rows) per plot.

The experiment involved a total of sixteen plots, with four replicate plots for each of the four treatments, including: an open field control treatment (open field), and three management treatments consisting of (1) an open field push-

pull treatment, (2) a net house treatment and (3) a combined net house + push-pull strategy treatment. Plots were laid out in a Latin square design with four replicates (Figure 1). The treatment 1 plots included two repellent plants, lemongrass and Mexican marigold as push components (Calumpang et al., 2013) and coloured sticky traps (blue and yellow) as pull components (Webb et al., 1994; Muvea et al., 2014). Mexican marigold was planted at 20 cm intervals and lemongrass at 2 m intervals around the plots. Mexican marigold served as a repellent plant via its continuous release of repellent volatiles. Moreover, on the basis of previous findings that volatiles emitted by freshly cut lemongrass leaves were effective in repelling *M. sjostedti* for 24 h (Diabate et al., 2019a), freshly cut lemongrass leaf pieces (about 5 cm of each leaf cut with scissors once a week) were also applied between the rows as organic mulch to repel *M. sjostedti* and *A. craccivora*. In the treatment 3 plots, Mexican marigold was planted outside the net house to discourage insects from passing through the net and lemongrass was planted inside the net house along the sides to repel insects that managed to enter. The experimental plots were separated from each other by 2-m buffer strips of bare soil. Blue sticky traps were used to catch *M. sjostedti* and yellow sticky traps served to capture other insects including whiteflies and aphids. Four strips of sticky tape (15 cm × 10 m) per push-pull plot were placed at 1 m intervals between the rows, 1 m above the soil and attached to sticks fixed to the ground. The traps were removed and replaced with new ones monthly over the 4-month cowpea cropping period. Insects on 10×10 cm samples of each replaced trap were then counted in the laboratory. No chemical insecticide treatments were carried out during in the field experiment, but a biopesticide—a mixture of 5 ml of liquid soap and 5 g of pepper powder in 20 l of water—was applied when a threshold of 1,000 aphids per plant was reached on three plants/plot in net house treatments. This biopesticide was sprayed twice in all treatments (on 17 and 24 November 2017) to slightly reduce the aphid populations, since high *A. craccivora* infestation of cowpea plants can cause high plant mortality (Annan et al., 1994). Biopesticide sprays were conducted during the dry period to avoid infested plant loss during the field trial, but this was not done during the rainy period. This soap/pepper solution provides a safe means to reduce aphid populations (Poswal and Akpa, 1991; Pahla et al., 2014), but it is less effective than synthetic insecticides in open field conditions (Ahmed et al., 2019; Smaili et al., 2014). To the best of our knowledge, there are no reports of this biopesticide impacting any of the other insects sampled in the study.

2.3. Sampling methods of insects and yield

The insect pests were counted 2 weeks after sowing and thereafter on a weekly basis for 14 and 15 weeks during the dry and rainy periods, respectively. Two plants per row were randomly selected and 10 individual plants were monitored in 5 rows per plot, for a total of 160 plants monitored per sampling date. The first and last plants of each row were not used to avoid border effects. The insects were counted between 9 am and 3 pm in all plots. Adult and immature insects were visually counted on different parts of each cowpea plant—large insect pests such as leafhoppers, *Empoasca* sp., brown pod-sucking bugs, *C. tomentosicollis,* and larval bean pod borers, *M. vitrata*, were counted on whole plants. Small adult insects such as bean flower thrips, *M. sjostedti*, black legume aphids, *A. craccivora*, and greenhouse whiteflies, *Trialeurodes vaporariorum* Westwood, were counted on one old lower leaf and one young upper leaf per cowpea plant. *A. craccivora* and *M. sjostedti* were also counted on two picked open flowers, and on two pods per plant. *A. craccivora* was counted on a 5 cm portion of the plant stem (the number of insects counted on 1 cm were multiplied by 5 cm representing the portion of the plant stem).

The number of flowers and pods were counted on 10 plants randomly selected per plot. The harvested pods, undamaged pods or pods damaged by insects were counted and weighed to evaluate the quantity of marketable pods. Cowpea grains harvested on each plot were placed in bags and weighed on a mechanical kitchen scale.

2.4. Data analysis

The data were systematically log transformed (log (x+0.5) to ensure homogeneity of variance and conformation to normality before using a linear mixed model with random intercepts. Treatments were considered as fixed factors while plots were random factors. The model was fitted using the *lmer* function from the *lme4* package (Bates et al., 2015), and the fixed factor effects were tested using Type II Wald F tests. When the tests revealed a significant treatment effect, means were separated by least squares means (lsmeans) adjusted using the Tukey method. Between-period comparisons of insects counted on sticky traps and treatments were performed via Student's t tests after transformation. R version 3.3.2 software (R Core Team, 2016) was used for all analyses.

3. Results

3.1. Colonization of plants by small insect pests in both dry and rainy periods

In the dry period, cowpea colonisation by insects with piercing-sucking mouthparts such as *T. vaporariorum* and *A. craccivora* started in the control and treatment 1 experiments (open field) 2 and 3 weeks after sowing, respectively

(Figure 2a, 2b). *A. craccivora* infestations were low in the open field treatments compared to the treatments 2 and 3. *T. vaporariorum* was observed on leaves while *A. craccivora* was noted on leaves and stems during cowpea seedling stage and on flowers and pods during the reproductive stage. Peak *T. vaporariorum* infestations were detected 6 weeks after sowing in the control plots, whereas *A. craccivora* outbreaks peaked 8 and 9 weeks after sowing in the treatment 3 and 2 during the flowering and podding stages, respectively. *M. sjostedti* infestations started during the cowpea flowering stage 8 weeks after sowing in both open field treatments (Figure 2c).

In the rainy period, *T. vaporariorum, A. craccivora* and *M. sjostedti* infestations began in periods similar to those noted in the dry season treatments (Figure 3a, b, c). *T. vaporariorum* infestations peaked 6 weeks after sowing in the control plots, while *A. craccivora* infestations peaked 7 weeks after sowing in the control plots. Three *M. sjostedti* infestation peaks occurred 13, 14 and 15 weeks after sowing in the treatments 2, 1 and control plots, respectively.

3.2. Effects of dry and rainy periods on small insect pests

The between-period comparison showed that in the rainy period small insect pest populations were lower than or equal to those in the dry period (Table 1). In all treatments, the *M. sjostedti* population did not differ the dry and rainy periods. However, *A. craccivora* numbers were higher in the treatments 2 and 3 in the dry period than in the rainy period (treatment 2: $t = 2.186$, df = 114, $p = 0.030$; treatment 3: $t = 4.172$, df = 114, $p < 0.001$). Conversely, the *A. craccivora* population was higher in the control and treatments 1 in the rainy period than in the dry period (control $t = -1.899$, df = 114, $p = 0.059$; treatment 1: $t = -1.986$, df = 114, $p = 0.049$). In the control treatment ($t = 2.846$, df = 114, $p = 0.005$) and treatment 1 ($t = 4.010$, df = 114, $p < 0.001$), *T. vaporariorum* whitefly populations were higher in the dry period than in the rainy period.

3.3. Effects of each treatment on small insect pests

3.3.1. Megalurothrips sjostedti and *Aphis craccivora*

M. sjostedti populations did not vary among treatments in both periods (Table 1). *A. craccivora* infestations were higher in the treatments 2 and 3 than in control and treatment 1 during the dry period. Otherwise, *A. craccivora* infestations did not vary among treatments in the rainy period.

3.3.2. Trialeurodes vaporariorum

T. vaporariorum numbers were lower in the treatments 2 and 3 than in the open field treatments during the dry period. *T. vaporariorum* populations were higher in the control than in the treatments 2 and 3 in the rainy period.

3.4. Effects of dry and rainy periods on large insect pests

Infestations of the large insect pest *M. vitrata* were low infestations in all treatments, but they were significantly higher in the control during dry period than in the rainy period (t = 2. 810, df = 114, p = 0.005). *Empoasca* sp. numbers were found to be highest during the rainy period. *Empoasca* sp. infestations were higher in the open field treatments in the rainy period than in the dry period (control: t = -5.449, df = 114, p < 0.001; treatment 1: t = -4.273, df = 114, p < 0.001). *C. tomentosicollis* infestations were higher in the treatment 2 and 3 during the rainy period than during dry period (treatment 2: t = -2.457, df = 114, p = 0.015; treatment 3: t = -4.922, df = 114, p < 0.001).

3.5. Effects of each treatment on large insect pests

3.5.1. Maruca vitrata

M. vitrata infestations were lower in the treatment 2 than in the control during the dry period, but no differences were observed among treatments during the rainy period.

3.5.2. Empoasca sp.

Empoasca sp. infestations were lower in the treatments 2 and 3 than in both open field treatments during the dry period. *Empoasca* sp. numbers were higher in the control than in all other treatments during the rainy period. In addition, *Empoasca* sp. numbers in the treatment 1 were higher than in the treatments 2 and 3 but lower than in the control.

3.5.3. Clavigralla tomentosicollis

C. tomentosicollis infestations were lower in the treatments 2 and 3 than in control and treatment 1 during the dry period (Table 1). However, *C. tomentosicollis* numbers were higher in the treatment 3 than in the treatment 2 in the rainy period. *C. tomentosicollis* infestations in control and treatment 1 were not significantly different.

3.6. Pests caught by coloured sticky traps with the push-pull strategy

The yellow sticky traps caught higher *T. vaporariorum* numbers in the treatment 1 than in the treatment 3, but no differences were observed between these two treatments with blue sticky traps (Table 2). The blue sticky traps caught more *M. sjostedti* in the treatment 1 than in the treatment 3. No differences were observed in *M. sjostedti* numbers caught on the yellow sticky traps when comparing the treatments 1 with treatments 3. *A. craccivora* numbers caught on yellow and blue sticky traps did not differ between the treatments 1 and 3. Only winged aphids were caught on the traps, whereas mostly nonwinged aphids were detected on cowpea plants.

3.7. Influence of the planting period on yield parameters

There were no significant differences in the number of open flowers when comparing the same treatment in the two periods (Table 3). All yield parameters observed in the present study were lower in both of the open field treatments in the rainy period than in the dry period, including the total harvested pod number (control: $t = 4.486$, df = 114, $p < 0.001$; treatment 1: $t = 4.441$, df = 114, $p < 0.001$), the total harvested pod weight (control: $t = 4.469$, df = 114, $p < 0.001$; treatment 1: $t = 4.649$, df = 114, $p < 0.001$), marketable harvested pods (control: $t = 4.577$, df = 114, $p < 0.001$; treatment 1: $t = 4.518$, df = 114, $p < 0.001$) and the marketable harvested pod weight (control: $t = 4.528$, df = 114, $p < 0.001$; treatment 1: $t = 4.757$, df = 114, $p < 0.001$). On average, the harvested pod number in the open field treatments was 220-fold (control) and 55-fold (treatment 1) greater during the dry period compared to rainy period. No differences in yield parameters were observed between periods in both of the net house treatments.

3.8. Effects of treatments on crop yield

The open flower numbers did not differ among the treatments in both periods and nor any of the pod parameters differ among the treatments in the dry period (Table 3). However, the total harvested pods and their weight were 2-fold greater in the treatment 2 than in the control during the dry period. In addition, marketable harvested pods were 2-fold greater in the treatments 2 than in both of the open field treatments, while the marketable pod weights were 2-fold greater in the treatments 2 and 3 than in the control during the dry period. During the rainy period, the total harvested pods, harvested pod weight, marketable harvested pods and marketable pod and grain weights were greater in the treatments 2 and 3 than in the control and treatment 1. However, no differences were observed between the control and treatment 1 and between the treatment 2 and the treatment 3 during the rainy period. The grain quality in the plots was only assessed during the rainy period and the treatments 2 and 3 grain was better than that harvested in the open field treatments in the rainy period (Supplementary data).

256 **4. Discussion**

257 The present study showed that net house and net house + push-pull treatments were effective in protecting cowpea
258 crops against most of the major large insect pests present. Previous studies revealed effective protection of vegetable
259 crops grown in high or low tunnels under insect netting (Martin et al., 2015; Simon et al., 2014). For example, in
260 Benin, netting reduced diamond back moth, *Plutella xylostella* L., large cabbage white, *Pieris brassicae* L., cabbage
261 webworm, *Hellula undalis* Fabricius, and cotton bollworm *Helicoverpa armigera* Hübner, populations on cabbage
262 crops (Simon et al., 2014).

263 Here we found that *T. vaporariorum* and *M. sjostedti* populations on cowpea crops in the net house and net house +
264 push-pull treatments were always lower than in the control. The net house could work as a screen which disturbs the
265 visual cues used by these insects to locate their host plants. Gogo et al. (2014b) suggested that the bright white
266 colour of the nets could act as a visual barrier. Like many insects, whiteflies and thrips orient their movements
267 visually (Teulon et al., 1999; Antignus et al., 2001). Net houses reduce UV light penetration, which may in turn
268 interfere with insects' vision and dispersion under the net house (Raviv et al., 2004; Ben-Yakir et al., 2014). By
269 contrast, we found that *A. craccivora* infestations were higher in the net house and net house + push-pull treatments
270 than in open fields, particularly in the dry period. The aphid outbreaks that occurred in the net house in the dry
271 period suggest that the temperature and humidity conditions under this shelter were suitable for aphids. Net houses
272 are known to provide conditions conducive to aphid outbreaks, as reported with regard to *Lipaphis erysimi*
273 (Kaltenbach) infestations on cabbage crops in Benin (Simon et al., 2014), *Myzus persica* (Sulzer) and *Aphis gossypii*
274 (Glover) infestations on sweet pepper crops (Singh et al., 2004) grown under netting. Insect nets can also protect
275 aphid populations from parasitoids and predators (Martin et al., 2013). The absence of natural enemies to regulate
276 aphid populations in the net house and net house + push-pull treatments may explain the high *A. craccivora* numbers
277 observed in our study. Conversely, the presence of natural enemies in open field treatments could explain the
278 reduced *A. craccivora* numbers in the dry period—many adult and larval coccinellid beetles were actually observed
279 on plants in open field treatments. Spraying a soap/pepper biopesticide solution on the cowpea crops reduced aphid
280 populations in our study, in line with the findings of previous studies (Poswal and Akpa, 1991; Pahla et al., 2014).
281 Releasing predators or parasitoids inside the net house is another way to reduce *A. craccivora* infestations. Yang et
282 al. (2014) reported that the release of *Harmonia axyridis* (Pallas) natural enemies in the greenhouse was an effective

way to reduce *Aphis gossypii* Glover populations on strawberry and cucumber. The severe aphid infestations we noted on cowpea flowers and pods could explain why cowpea yields were not as high as expected in the net house and net house + push-pull treatments. The best cowpea yields were nevertheless obtained in the net house treatment compared to other treatments despite the *A. craccivora* outbreak. The M66 cowpea cultivar used in this study may be tolerant to *A. craccivora*, since this cowpea genotype was an improved variety from the Kenya Agricultural Livestock Research Organization (KALRO) which is partly tolerant to aphid damage (Kenya Agricultural Research Institute (KARI), 2008; Kimutai, 2017).

We also hypothesised that the combined use of netting and the push-pull strategy (treatment 3) could help control small insect pests, particularly thrips on bean flowers. In our study, lemongrass (*C. citratus*) and Mexican marigold (*T. minuta*) were used to repel (push) insects from the cowpea crop and sticky traps were used as attractants (pull) to catch the flying insects. In laboratory assays, *M. sjostedti* was shown to be repelled by fresh cut lemongrass leaves but not by old cut leaves (Diabate et al., 2019a), but *M. sjostedti* numbers did not vary among any of the treatments in our study. Lemongrass leaves were cut once a week and spread between the rows to repel thrips. In addition, *T. minuta* likely continuously released repellent volatiles that prevented *M. sjostedti* from locating the cowpea plants. The repellent effect of volatiles could have been of short duration or the cut lemongrass leaves were perhaps not sufficiently abundant to repel *M. sjostedti*. The fact that there was a greater abundance of cowpea plants relative to lemongrass and Mexican marigold plants in the field could mean that there was an overwhelming presence of attractive volatiles, thus decreasing repellent effect of the companion plants. The efficacy of repellent volatiles could be enhanced in the field by sowing companion plants that produce greater quantities of repellent volatiles, or otherwise repellent essential oils could be provided through dispensers or injected in the irrigation system. We previously identified repellent citral volatiles in lemongrass and repellent blends of dihydrotagetone, *(Z)*-3-hexenyl acetate, limonene and *(Z)-β*-ocimene volatiles in marigold (Diabate et al., 2019a). These compounds could be supplemented via dispensers to lengthen the repellence period in the field. Although the blue sticky traps were effective in catching *M. sjostedti* in the open field push-pull treatment, the number of thrips on cowpea plants in this treatment did not differ from that in the control. *M. sjostedti* was more attracted to cowpea flowers than to the blue traps. Frey et al. (1994) reported that the plant growth stage may have an impact on the efficacity of colour traps. For example, the number of *F. occidentalis* thrips caught on blue sticky traps in ornamental greenhouses was reported to be lower during flowering than during the vegetative stage (Frey et al., 1994).

By contrast, our findings showed that the *Empoasca* sp. population was lower in the open field push-pull treatment than in the control during the rainy period. Volatiles released by Mexican marigold and lemongrass could have been involved in the reduction of *Empoasca* sp. populations in the open field push-pull treatment. Calumpang et al. (2013) observed a reduction in green leafhopper, *Amrasca biguttula* (Ishida), populations when lemongrass was intercropped with eggplant. It was also reported that using Mexican marigold as an intercrop and maize as a border crop reduced *A. biguttula biguttula* leafhopper populations on eggplant crops in the field (Sujayanand et al., 2015). On the other hand, yellow sticky traps may contribute to reducing *Empoasca* sp. numbers. The attraction of sharp-nosed leafhoppers, *Scaphytopius magdalensis* (Provancher), to yellow traps was also demonstrated by Rodriguez-Saona et al. (2012). Combining visual and olfactory cues in a push-pull strategy could prove effective in controlling *Empoasca* sp. populations.

The open field push-pull treatment did not have an impact on insect populations except *Empoasca* sp. and therefore did not increase the pest control efficacy of the net house + push-pull treatment in the present study. Several authors have demonstrated the efficacy of non-host plant volatiles in reducing insect populations in the field (Parolin et al., 2012), whereas many other studies failed to reveal their efficacy in the same conditions (Held et al., 2003; Webster and Cardé, 2016). For example, intercropping French marigold, a non-host plant, with host potato plants did not reduce Colorado potato beetle, *Leptinotarsa decemlineata* (Say), populations but conversely it increased the incidence of *L. decemlineata* attacks (Moreau et al., 2006). In our study, we observed no such perverse effects of the push-pull strategy on any cowpea pests.

We observed that cowpea yields and insect populations varied with the period. Populations of large insect pests were higher in the rainy period than in the dry period. Conversely, small insect pests such as *M. sjostedti*, *T. vaporariorum* and *A. craccivora* were much lower in the rainy period than in the dry period. In Kenya, the heavy rainfall between March and June 2018 may have been responsible for the reduction in insect populations via egg destruction and partial larval mortality. Nyasani et al. (2013) reported that heavy rain destroyed western flower thrips, *F. occidentalis,* larvae in the field and hence reduced their population density. In our study, *A. craccivora* populations were reduced in the net house and net house + push-pull treatments in the rainy period compared to the dry period. The top of net house was flat and rain penetrated through the mesh. Rainfall is considered to regulate aphid population densities (Kaakeh and Dutcher, 1993). The lower aphid numbers in the net house and net house +

push-pull treatments suggest that the microclimate was unsuitable for these pests during the rainy period. Rainfall increased the relative humidity under the net, which could have a negative impact on *A. craccivora* populations by enhancing the environmental conditions for entomopathogenic fungi. Kataria and Kumar, (2017) reported that *A. craccivora* population patterns were negative correlated with minimum temperature, relative humidity and rainfall. In addition, *A. craccivora* propagate parthenogenetically in Africa (Irwin, 1980). This asexual reproduction enables aphids to multiply and spread rapidly under optimal conditions (Iluz, 2011). However, conditions might be different in the future and the lack of gene combinations could be a disadvantage to the offspring, thus curbing the growth populations of this pest. Cowpea pod yields in the open field treatments were very poor during the rainy period compared to the dry period. The reduction in pod yield may have been due to excessive rainfall in the rainy period, as already observed by Parwada (2016). In addition, cowpea plants in the open field treatments were heavily damaged by fungi and diseases in the rainy period. Edema et al. (1997) reported a higher incidence and severity of viral diseases, anthracnose and scab on cowpea crops in the rainy period than in the dry period. Fungi such as cercospora leaf spot may affect cowpea pod production and quality. Our study showed that net houses could help farmers to produce cowpea intensively. Despite the fact the rainy period was longer than usual during our study, cowpea production was always higher in the net house and net house + push-pull treatments than in the open field conditions. Net technology thus seems to be an efficient tool to help farmers grow vegetables in unpredictable weather conditions.

During both climate periods, all yield parameters evaluated were higher in the net house and net house + push-pull treatment than in the open field. The net house protected cowpeas against large insect pests or had no special effect on some of them, except in the rainy period when a *C. tomentosicollis* infestation was observed in the net house + push-pull treatment. Our findings did not enable us to explain why the *C. tomentosicollis* population was high in the net house + push-pull treatment in the rainy period, but the high density of Mexican marigold plants around the net house might have attracted or protected them. Further investigations are needed to elucidate this issue. Despite, the abundance of *Empoasca* sp. in the open fields during the rainy period, the net houses (used in treatments net house and net house + push-pull) prevented this pest from infesting the cowpea crops in the rainy period. The use of net houses in horticulture usually has a major impact on crop yields by reducing populations of large insect pests. *M. vitrata* and *C. tomentosicollis* can cause cowpea yield losses of up to 80% in Africa (Ekesi et al., 2002; OECD, 2015). The reduction of large insect pests could thus partially explain the increased crop yield in the net house and

net house + push-pull treatments, whereas the modified microclimate in the net house could boost plant development. Saidi et al. (2013) reported that the constant high temperature and soil moisture in net houses improved plant growth and yield. Moreover, we noticed that the quality of the grains produced in the net house and net house + push-pull treatments were higher. In Kenya, Gogo et al. (2014) also reported faster development, higher pod yield, and better quality of green beans, another leguminous plant that was grown under low netting covered tunnels as compared to uncovered plants.

In our study, the cowpea pod numbers were higher in the dry period than in the rainy period. Conditions in the dry period were better for cowpea pod production compared to the rainy period. Cowpea is an herbaceous warm-season annual and many authors have reported its good adaptation to high temperatures and drought (Ehlers and Hall, 1997; Timko et al., 2007). Moreover, the reduction of large insect pests in the dry period consequently reduced cowpea flower and pod damage due to low feeding activity. Conversely, small insect pests were more abundant in the dry period. Populations of *M. sjostedti* thrips and *T. vaporariorum* whiteflies on cowpea plants in the net house and net house + push-pull treatments were always lower than the open field populations, which increased very rapidly, particularly in the dry period. *M. sjostedti* outbreaks were linked to the flower emergence. *M. sjostedti* preferentially feeds on flowers, causing them to fall (Moritz et al., 2013). However, there was no difference in the total number of pods and flowers among the different treatments in the dry period. The high *A. craccivora* infestation of cowpea vegetative parts, flowers and pods in the net house and net house + push-pull treatments did not decrease yields in the dry period. Small insect pests therefore seem to have a limited impact on cowpea production, contrary to large insect pests.

5. Conclusion

The findings of this study showed that net house and net house + push-pull treatments considerably reduced pest infestations on cowpeas and that the damage was mainly incurred by large insect pests such as *Empoasca* sp., *M. vitrata* and *C. tomentosicollis* along with smaller insect pests such as *M. sjostedti* and *T. vaporariorum*. We also noted that net house grown cowpeas could be subject to high *A. craccivora* infestation. Aphid outbreaks seemed to have a limited impact on cowpea yields, so populations of this pest could be reduced by biopesticide treatment. The net house + push-pull treatment did not improve *T. vaporariorum*, *A. craccivora* and *M. sjostedti* control. However, the open field push-pull treatment reduced *Empoasca* sp. infestations during the rainy period. The study also showed

that cowpea production was much higher in the net house and net house + push-pull treatments than in the open field. In addition, cowpea pod yields were higher in all treatments during the dry period than in the rainy period. The large insect pest populations were low during the dry period and high in the rainy period, contrary to small insect pest populations. The study showed that cowpea production was impacted by the period and large insect pest infestations. This study showed that netting technology provides an effective alternative to chemical pesticide treatments for vegetable growing in the tropics regardless of the season. We showed that netting technology could be slightly improved to control sucking insect pests using the push-pull strategy. Cowpea yields were highly affected by heavy rains in both open field treatments but not in the net house and net house + push-pull treatments. Future research should be focused on investigating the effect of microclimate and insect pests on cowpea yield in net houses. In Mwea (Kenya), the rainy season is not the best period to grow cowpeas in the open fields despite the low insect pest pressure. But we found that the cowpea yield and quality in the net house treatment was still high, thus confirming the need for netting to produce off-season vegetable crops when prices may be higher due to the low market supply. This study confirmed that netting is an efficient tool for protecting vegetable crops against insect pests and producing higher yields of safe vegetables.

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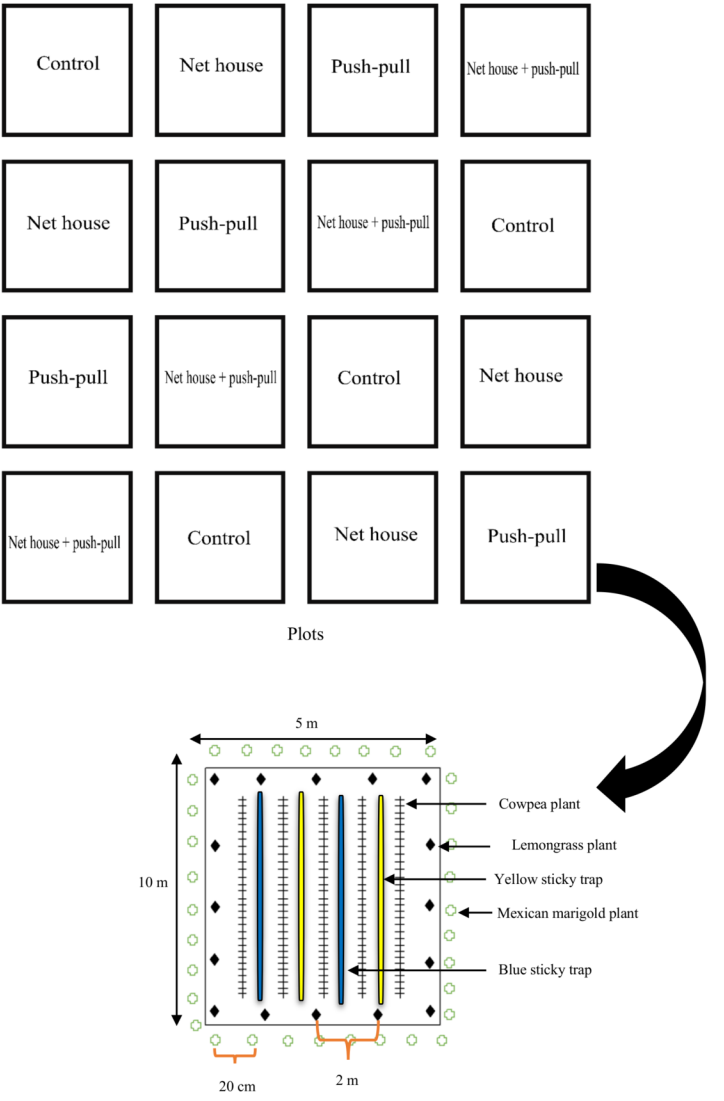
Figure captions

Figure 1: Schematic representation of the experimental field set up in a 4x4 Latin square design with a total of 16 plots and randomized rows and columns. 300 plants were grown per plot and plots were separated by 2-m bare soil buffer strips. Four strips of sticky tape (15 cm x 10 m) per push-pull plot were placed at 1 m intervals between the rows.

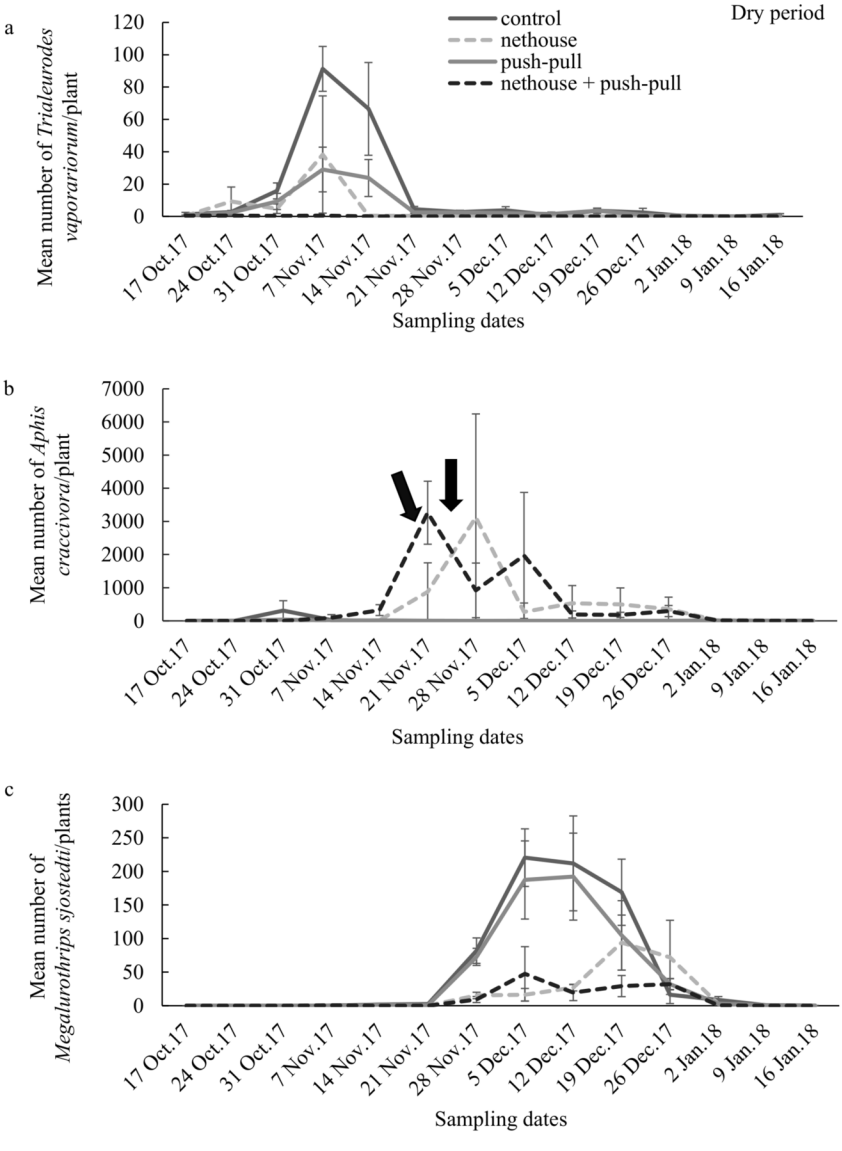
Figure 2: Effects of treatments on adult *Trialeurodes vaporariorum (a)*, adult and larval *Aphis craccivora* (b), adult and larval *Megalurothrips sjostedti* (c) population fluctuations in the dry period at KALRO-Mwea (Kenya).

➡ Two applications of a mixed pepper/soap solution in all treatments on 17 and 24 November 2017

Figure 3: Effects of treatments on adult *Trialeurodes vaporariorum*, adult and larval *Aphis craccivora,* adult and larval *Megalurothrips sjostedti* population fluctuations in the rainy period at KALRO-Mwea (Kenya).



A push-pull treatment plot


a
Dry period
control
nethouse
push-pull
nethouse + push-pull
Mean number of Trialeurodes vaporariorum/plant
120
100
80
60
40
20
0
17 Oct.17
24 Oct.17
31 Oct.17
7 Nov.17
14 Nov.17
21 Nov.17
28 Nov.17
5 Dec.17
12 Dec.17
19 Dec.17
26 Dec.17
2 Jan.18
9 Jan.18
16 Jan.18
Sampling dates
b
Mean number of Aphis craccivora/plant
7000
6000
5000
4000
3000
2000
1000
0
17 Oct.17
24 Oct.17
31 Oct.17
7 Nov.17
14 Nov.17
21 Nov.17
28 Nov.17
5 Dec.17
12 Dec.17
19 Dec.17
26 Dec.17
2 Jan.18
9 Jan.18
16 Jan.18
Sampling dates
c
Mean number of Megalurothrips sjostedti/plants
300
250
200
150
100
50
0
17 Oct.17
24 Oct.17
31 Oct.17
7 Nov.17
14 Nov.17
21 Nov.17
28 Nov.17
5 Dec.17
12 Dec.17
19 Dec.17
26 Dec.17
2 Jan.18
9 Jan.18
16 Jan.18
Sampling dates

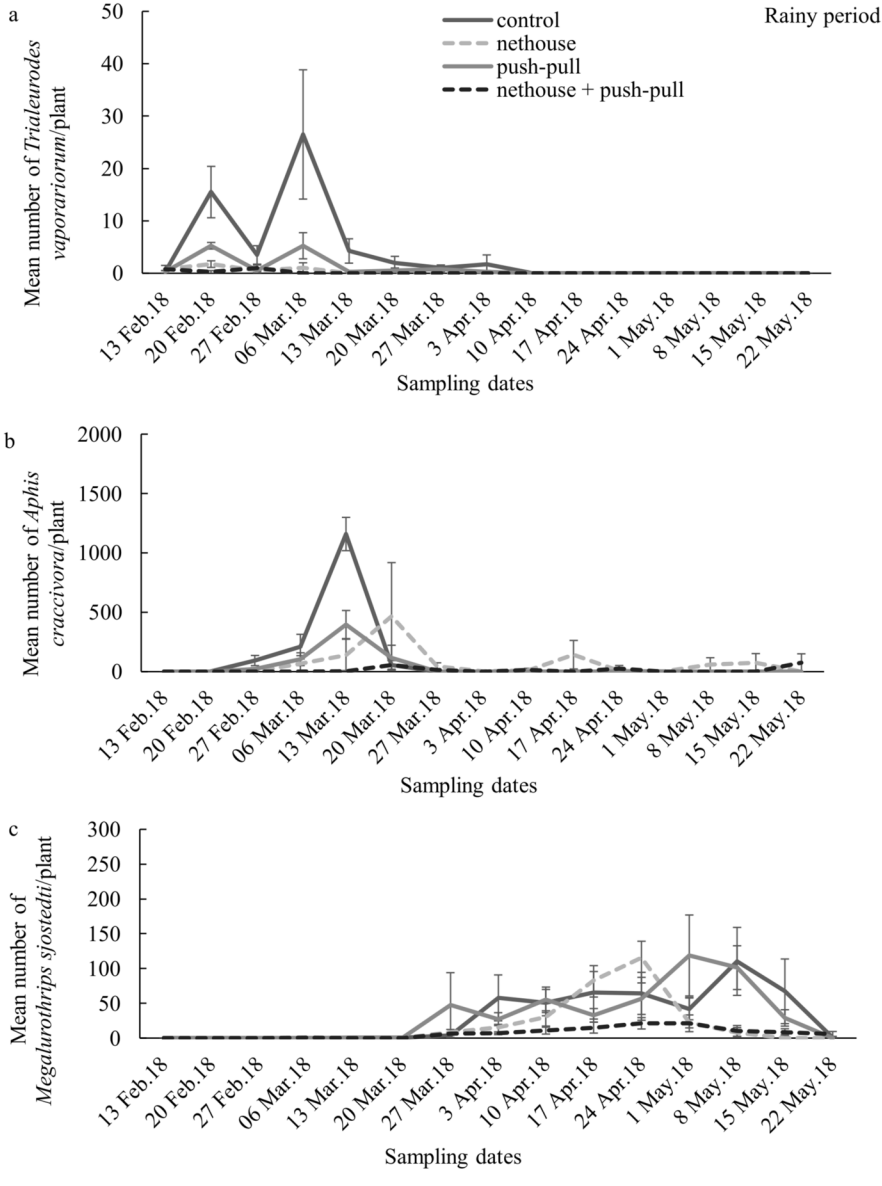

a
Rainy period
control
nethouse
push-pull
nethouse + push-pull
Mean number of Trialeurodes vaporariorum/plant
50
40
30
20
10
0
13 Feb.18
20 Feb.18
27 Feb.18
06 Mar.18
13 Mar.18
20 Mar.18
27 Mar.18
3 Apr.18
10 Apr.18
17 Apr.18
24 Apr.18
1 May.18
8 May.18
15 May.18
22 May.18
Sampling dates
b
Mean number of Aphis craccivora/plant
2000
1500
1000
500
0
13 Feb.18
20 Feb.18
27 Feb.18
06 Mar.18
13 Mar.18
20 Mar.18
27 Mar.18
3 Apr.18
10 Apr.18
17 Apr.18
24 Apr.18
1 May.18
8 May.18
15 May.18
22 May.18
Sampling dates
c
Mean number of Megalurothrips sjostedti/plant
300
250
200
150
100
50
0
13 Feb.18
20 Feb.18
27 Feb.18
06 Mar.18
13 Mar.18
20 Mar.18
27 Mar.18
3 Apr.18
10 Apr.18
17 Apr.18
24 Apr.18
1 May.18
8 May.18
15 May.18
22 May.18
Sampling dates

Table 1: Mean (± SE) and abundance of insects observed per plant among the treatments in the dry period[1] and rainy period[2] at KALRO- Mwea (Kenya).

		Dry period						Rainy period					
	Insect pests	Control	Treatment 1	Treatment 2	Treatment 3	F	P-value	Control	Treatment 1	Treatment 2	Treatment 3	F	P-value
small pests	*Megalurothrips sjostedti*	51.0 ± 12.6 a	42.6 ± 11.2 a	16.3 ± 5.8 a	9.9 ± 3.7 a	2.54	0.10	31.4 ± 7.2 A	31.3 ± 7.1 A	18.8 ± 5.1 A	7.1 ± 1.5 A	1.67	0.22
	Aphis craccivora	24.6 ± 21.5 a*	5.10 ± 2.8 a*	406.5 ± 213.08 b*	518.8 ± 191.5 b*	17.33	P < 0.001	101.3 ± 39.0 A*	43.0 ± 16.5 A*	67.7 ± 32.9 A*	12.5 ± 6.0 A*	1.20	0.34
	Trialeurodes vaporariorum	14.0 ± 4.2 a*	5.6 ± 1.7 a*	3.8 ± 2.7 b	0.1 ± 0.1b	18.54	P < 0.001	3.7 ± 1.2 A*	1.0 ± 0.3 AB*	0.3 ± 0.1 B	0.1 ± 0.1 B	9.37	0.0018
large pests	*Maruca vitrata*	0.3 ± 0.1 a*	0.2 ± 0.1 ab	0 b	0.0 ± 0.0 ab	4.43	0.025	0 A*	0.0 ± 0.0 A	0A	0A	2.45	0.11
	Empoasca sp.	0.4 ± 0.1 a*	0.3 ± 0.1 a*	0 b	0.0 ± 0.0 b	8.77	0.002	8.0 ± 1.6 A*	3.1 ± 0.7 B*	0.1 ± 0.1 C	0 ± 0 C	35.62	P < 0.001
	Clavigralla tomentosicollis	7.5 ± 3.0 a	5.6 ± 2.5 a	0.2 ± 0.2 b*	0 b*	9.41	0.001	2.7 ± 0.8 AB	4.2 ± 1.2 AB	2.4 ± 1.3 A*	10.0 ± 2.5 B*	3.68	0.043

[1] From 3 October 2017 to 9 January 2018; [2] From 30 January 2018 to 15 May 2018, SE = Standard error, numerator and denominator degrees of freedom (df = 3, 12). Treatment 1= Push-pull strategy; Treatment 2 = Net house; Treatment 3 = Combined net house + push-pull strategy. Small letters correspond to the comparison of treatments in the dry period and capital letters refer to the comparison of treatments in the rainy period using a linear mixed model (F, p-value). If significant, means were separated by least squares means (lsmeans) adjusted using the Tukey method. *indicates significant differences between the same treatment in the two periods according to the Student's t test. The same letter in the same row means not different.

Table 2: Mean (± SE) number of insects: *A. craccivora, M. sjostedti* and *T. vaporariorum* caught on the coloured sticky traps during the two periods. Dry period from 3 October 2017 to 9 January 2018. Rainy period from 30 January 2018 to 15 May 2018.

Insects		Blue trap	Yellow trap
T. vaporariorum	Treatment 1	10.6 ± 12.8a	2315.3 ± 1771.5a
	Treatment 3	1.0 ± 2.0a	91.2 ±100.0b
	t-test	*1.438*	*2.583*
	P value	*0.172*	*0.021*
M. sjostedti	Treatment 1	265.4 ± 131.7a	4.4 ±4.5a
	Treatment 3	27.0 ± 14.2b	2.1 ±1.4a
	t-test	*3.487*	*0.241*
	P value	*0.003*	*0.812*
A. craccivora	Treatment 1	0a	64.6 ± 99.9a
	Treatment 3	0.25± 0.32a	93.9 ± 88.6a
	t-test	*-1.527*	*-0.993*
	P value	*0.148*	*0.337*

SE = Standard error, df= 14. Treatment 1 = Push-pull strategy; Treatment 3 = Combined net house + push-pull strategy. Small letters refer to the comparison of two treatments per insect in each column using the Student's t test at $p < 0.05$. The same letter means not significantly different

Table 3: Mean (± SE) flowers per plant, the total and weight of harvested pods, marketable weight of harvested pods and number of grains per plot among the treatments in the dry period[1] and rainy period[2] at KALRO- Mwea (Kenya).

	Dry period						Rainy period					
	Control	Treatment 1	Treatment 2	Treatment 3	F	P-value	Control	Treatment 1	Treatment 2	Treatment 3	F	P-value
Flowers	2.9 ± 0.7 a	5.8 ± 2.0 a	3.7 ± 0.9 a	3.2 ± 0.9 a	0.13	0.93	1.7 ± 0.4 A	2.5 ± 0.5 A	3.3 ± 0.7 A	3.1 ± 0.5 A	1.02	0.41
Total harvested pods	110.3 ± 30.3 a*	120.8 ± 31.7 a*	181.60 ± 49.6 a	149.4 ± 39.1 a	0.18	0.90	0.5 ± 0.5 A*	2.2 ± 1.7 A*	105.3 ± 26.3 B	73.9 ± 17.8 B	11.63	P < 0.001
Total weight of pods (g)	282.4 ± 78.4 a*	288.9 ± 73.7 a*	478.2 ± 131.7 a	403.9 ± 101.6 a	0.16	0.91	1.3 ± 1.3 A*	3.0 ± 2.7 A*	276.6 ± 70.4 B	187.2 ± 44.7 B	11.84	P < 0.001
Marketable harvested pods	70.6 ± 19.1 a*	75.4 ± 20.4 a*	156.8 ± 43.4 a	124.3 ± 32.1 a	0.31	0.81	0 A*	1.0 ± 0.7 A*	104.9 ± 26.0 B	69.4 ± 16.4 B	13.32	P < 0.001
Marketable weight pod (g)	198.2 ± 53.6 a*	201.1 ± 51.4 a*	431.1 ± 119.9 a	348.9 ± 86.2 a	0.29	0.83	0 A*	0.3 ± 0.3 A*	272.3 ± 68.7 B	181.7 ± 43.5 B	13.62	P < 0.001
Grains							0.7 ± 0.7 A	0.8 ± 0.7 A	227.5 ± 57.3 B	136.2 ± 33.1 B	12.28	P < 0.001

[1] From 3 October 2017 to 9 January 2018; [2]From 30 January 2018 to 15 May 2018, SE = Standard error, numerator and denominator degrees of freedom (df = 3, 12). Treatment 1 = Push-pull strategy; Treatment 2 = Net house; Treatment 3 = Combined net house + push-pull strategy. Small letters refer to the comparison of treatments in the dry period and capital letters to comparison of treatments in the rainy period using a linear mixed model (F, p-value). If significant, means were separated by least squares means (lsmeans) adjusted using the Tukey method. *indicates significant differences between the same treatment in the two periods with the Student's t test. The same letter in the same row means not different