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Night-time light-traps and push–pull integrated system enhanced the control of different life stages of fall armyworm, *Spodoptera frugiperda*, (Lepidoptera: Noctuidae)

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Abstract

Background Maize, Zea mays L (Cyperales: Poaceae), is one of the major cereal crops grown in Ethiopia for its food and feed values. Recently, the fall armyworm (FAW) (Spodoptera frugiperda) has become a major challenge of maize production threatening smallholder farmers in the country. Developing effective and smallholder farmers-friendly integrated pest management for FAW is vital. Therefore, a study was conducted to evaluate the effect of night-time light-traps and push–pull integrated system on controlling different life stages (adult, larvae and eggs) of FAW.

Methods The study was conducted in Northern Ethiopia included four treatments; maize monocrop, maize plots with night-time light-trap, a push–pull system, and night-time light-trap and push–pull integrated system. Each treatment was replicated five times. The study was carried out twice involving a rain feed (from July to October 2018) and irrigated (from April to June 2019) experiments.

Results A significantly greater number of FAW moths were captured on traps placed outside maize field plots treated with light-trap and push–pull integrated system than traps placed outside the maize monocrop, light-trap alone and push–pull alone treated plots during the 2018 and 2019 experiment seasons. As a result, a significantly lower number of moths was found inside maize field plots treated with light-trap and push–pull integrated system than the other treatments. The levels of FAW eggs and larval infestation were significantly lower in maize plots treated with the light-trap and push–pull integrated system than the maize monocrops, push–pull alone, and light-trap alone treated plots. The proportion of plants damaged by FAW larvae was significantly lower in maize plots treated with the light-trap and push–pull integrated system relative to maize plots treated with the other treatments.

Conclusion This study proved that a system integrating night-time light-traps and push–pull results in better and more effective control of different stages of FAW than a push–pull system or night-time light-traps alone.

Keywords Fall armyworm (FAW), Night-time light-traps, Push–pull system, Push-plant, Pull-plant

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Background

Maize, *Zea mays* L (Cyperales: Poaceae), is one of the major cereal crops grown worldwide including in sub-Saharan African countries (FAO 2018; Hailu et al. 2018; Midega et al. 2018; Kassie et al. 2020). It is the third most important agricultural commodity worldwide after rice and wheat in terms of cultivated area and consumption, being used for human consumption, animal feed, and as input for industrial processing (FAO 2018). In sub-Saharan Africa alone, more than 300 million people depend on maize production (Hailu et al. 2018). Similarly, it is one of the major cereal crops in Ethiopia, being a major stable food and feed source for millions of people in the country (Waktole and Amsalu 2012; Shiberu 2013; Abate et al. 2015; Tefera et al. 2016; Gebreziher and Gebreziher 2020). The country produces more maize than other crops, accounting for more than 27% of the crop production (Kumela et al. 2019). Maize is widely produced in almost all agro-ecosystems with both rain-based and artificial irrigation systems and smallholder-farmers accounting for the largest share of its production.

Although the crop plays a leading role in maintaining food security for the growing population, productivity remains low with an average yield of 3.24 tons ha^{-1} compared to the world average of 4.5 tons ha^{-1} (Kumela et al. 2019). The low productivity of maize in the country is attributed to both biotic (mainly diseases, weeds, and insect pests) (Waktole and Amsalu 2012; Tefera et al. 2016) and abiotic factors such as inefficient production methods, low soil fertility, drought, and small landholding (Abate et al. 2015; Kumela et al. 2019; Geta et al. 2013).

Among the biotic factors, pests such as the fall armyworm (FAW), *Spodoptera frugiperda* JE Smith (Lepidoptera: Noctuidae), different species of stemborers like *Chilo partellus* Swinhoe (Lepidoptera: Crambidae), *Busseola fusca* Fuller (Lepidoptera: Noctuidae) and *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae), and the notorious weed Striga, *Striga hermonthica* Benth (Lamiales: Orobanchaceae) are predominantly affecting maize production and productivity (Hailu et al. 2018; Midega et al. 2018; Gebreziher 2020a). Among these, FAW has become one of the major challenges of maize production mainly threatening smallholder farmers in the country (Gebreziher and Gebreziher 2020; Kumela et al. 2019; Day et al. 2017; FAO 2018b; Kebede and Out-break 2019; Sisay et al. 2019).

In Africa, FAW has become an invasive species in the last few years with outbreaks reported in western and central Africa in 2016 (Hailu et al. 2018; Day et al. 2017; FAO 2018b; Kebede and Out-break 2019; Abrahams et al. 2017; Midega et al. 2017; Baudron et al. 2019). Further spread of FAW was observed in Eastern and Southern African countries in 2017 (Gebreziher 2020a; Midega et al. 2017) and by late 2018, it had been confirmed by virtually every country in sub-Saharan Africa (Gebreziher 2020a; FAO 2018b; Hruska 2019). The spread of FAW within a country and among the African countries was rapid. For example, within Ethiopia, FAW infestations were reported in the Southern Nations, Nationalities, and Peoples` State on March 2017 and spread fast to all states to become an epidemic pest by June 2017 (FAO 2018b). Since then, the FAW has become a major pest of maize in all states of Ethiopia. Future forecasts predicted for the high possibility of this insect pest to become and remain a regular pest in Ethiopia and the continent (Day et al. 2017; Kebede and Out-break 2019; Midega et al. 2017).

The FAW, believed to be originated in the tropics and subtropics of America, causes damage to almost 100 plant species (Midega et al. 2017; Baudron et al. 2019; Hruska 2019; Andrade et al. 2000; Gichuhi et al. 2020). It mainly prefers maize, but it is also common on sorghum, rice, and millets, and is sporadically important on a vast array of additional crops and plants, including cotton and vegetables (Hruska 2019). It reproduces during the rainy season, during which the moths lay their eggs on crops. Their larvae march in groups, devouring food sources they come across. They subsequently pupate to form moths, each of which can fly up to 1,000 km and lay 1,000–2,000 eggs in their 10-day lifetime (Malo et al. 2002, 2004; Guerrero et al. 2014; Westbrook et al. 2016).

Given its voracious feeding habit, long-distance migration behavior and high reproductive rate, FAW might substantially and persistently affect many millions of smallholder farmers in the African continent unless cost-effective integrated pest management (IPM) approaches are in place to keep the pest below an economic threshold. While most farmers affected by FAW in developed countries have large-scale farm operations with access to international market prices, risk-transfer mechanisms and the benefits of government subsidies (Hruska 2019), the overwhelming majority of farmers in Africa are smallholders (Gebreziher and Gebreziher 2020; Gebreziher 2020a; Hruska 2019) without access to those conditions (Hruska 2019). This dramatically different context means that different management approaches must be sought. Therefore, developing effective and smallholder-farmers-friendly integrated FAW management strategies is of paramount importance. One of the management methods that are believed to be affordable by smallholder farmers is a push–pull system (Midega et al. 2018; Gebreziher 2020a; Khan et al. 2018; Alkema et al. 2019).

The push–pull system is a novel tool for IPM programs which uses a combination of behavior-modifying stimuli to manipulate the distribution and abundance of insect pests and/or natural enemies (Midega et al. 2018, 2015a; Gebreziher 2020a; Khan et al. 2018; Holdrege 2012; FAO 2016; Khan and Pickeet 2015; Bhattacharyya 2017). It involves intercropping target crops like maize with a repellent plant, such as silver-leaf desmodium, *Desmodium uncinatum* Jacq. (Fabales: Fabaceae) (a push-plant) that repels or deters insect pests, and planting an attractive trap plant which is highly apparent and attractive to a pest, such as Sudangrass, *Sorghum sudanense* Piper (Cyperales: Poaceae) or Napier grass, *Pennisetum purpureum* Schum. (Cyperales: Poaceae) (pull-plants), as a border crop around the intercropped field, thus, facilitating their accumulation and control (Midega et al. 2018, 2017; Gebreziher 2020a, 2020b; Cook et al. 2007; Khan et al. 2011; Poveda and Kessler 2012; Harrison et al. 2019). Recent findings reported that the push–pull system reduces FAW infestation in maize fields (Hailu et al. 2018; Midega et al. 2018; Kassie et al. 2020).

However, instead of using a push–pull system as a stand-alone control method of FAW, integrating with other monitoring and control mechanisms might enhance effective control of all life stages of FAW. An IPM approach would be more effective in sustainably containing and controlling FAW in maize by smallholder farmers. Previous findings reported that moths (both male and female) of many lepidopteran species including FAW are characterized by their rapid positive response to light during the night-time (Beck and Linsenmair 2006; Fayle et al. 2007; Nowinszky et al. xxxx). Night-time light-traps can be used for monitoring and mass trapping of lepidopteran moths including FAW (Fayle et al. 2007; Nowinszky et al. 2017). As an FAW IPM approach, we hypothesized that integrating night-time light-traps as monitoring and mass-trapping method with the push–pull system could provide better control of different life stages (adults, eggs, and larvae) of FAW. Therefore, the aims of this research were to: (1) determine the effect of integrating night-time light-traps with push–pull system on deterring FAW moths, (2) evaluate the effect of integrating night-time light-traps and push–pull system on FAW eggs and larvae infestation on maize plants, and (3) determine the proportion of maize plants damaged by FAW larvae in a night-time light-trap and push–pull integrated system treated maize plants relative to push–pull or light-trap alone treated maize plants as well as maize monocrops.

Materials and methods

Study area

The study was conducted in Hawzien Woreda (Woreda: Administrative unit below Zonal level), Hatset Kebele (Kebele: a small administrative unit below Woreda level), Northern Ethiopia. The study area is located at an elevation of 1800–2105 m.a.s.l and receives an annual rainfall of up to 500 mm year^{-1} and temperature range of 18–28 °C. Like the other districts of the Northern Ethiopia, the communities in the study area are dependent on mixed agriculture involving crops such as wheat, maize, sorghum, and barley and livestock production. The area was selected because it has been greatly affected by FAW since 2017, damaging maize crops of the smallholder farmers. The experimental site consisted of maize crop fields. The farmers in the area produce maize twice a year through rain feed and irrigation. Therefore, to complement this, the study was carried out twice involving a rain feed (from July to October 2018) and irrigated (from April to June 2019) experiments.

Materials

Planting materials

Maize (*Zea mays* L.; Variety: Melkassa-1Q) was used as the main crop for the study. Silver-leaf desmodium (*Desmodium uncinatum* Jacq.; Fabales: Fabaceae) as a repellent plant (push-plant) and Sudangrass (*Sorghum sudanense* Piper; Cyperales: Poaceae) as a trap plant (pull-plant) were used in the push–pull and light-push–pull treatments. The seeds of silver-leaf desmodium were obtained from Aksum Agriculture Research Center, Aksum, Ethiopia and seeds of Sudangrass were obtained from Wukro Agriculture College, Wukro, Ethiopia. Maize seeds were obtained from Hawzien Woreda Seed Distribution Office, Hawzien, Ethiopia.

Traps/Light-traps

Solar-charged light (d.light, S2 Lamp: 3.2 V, 72–93 mA) was used as a night-time light source for the light-trap and light-push–pull treatments. The light-trap was designed in a way involving the d.light in an adhesive cylindrical transparent plastic container (trap size: 15 cm diameter, 30 cm height) applied with molasses (as adhesive material) on both sides (from inside and outside) and hanged at 1.5 m height in a wooden robe. For monocrop treatments, traps with the same design as described in this section but without d-light (lightless traps) were used. In all treatments, the traps were replaced every two weeks.

Treatments and experimental design

The experiment had four treatments involving; (1) monocrop plots (maize crops only), (2) night-time light-traps treated maize plots (with night-time light-traps placed at edges), (3) push–pull treated maize plots (silver-leaf desmodium intercropped with maize and Sudangrass planted at all edges of maize plots), and (4) maize plots treated with night-time light-trap and push–pull integrated system. Each treatment was replicated five times. The treatments were laid out using a Completely Randomized Design (CRD) (Fig. 1). The distance between consecutive plots was 3 m. The four treatments are described as follow;

Monocrop plots: This involves plots with maize plants and lightless traps placed at edges of a maize plot (plot size: 4 m by 3 m). Maize seeds were planted at 0.5 m and 0.5 m inter- and intra-row spacing, respectively, in four

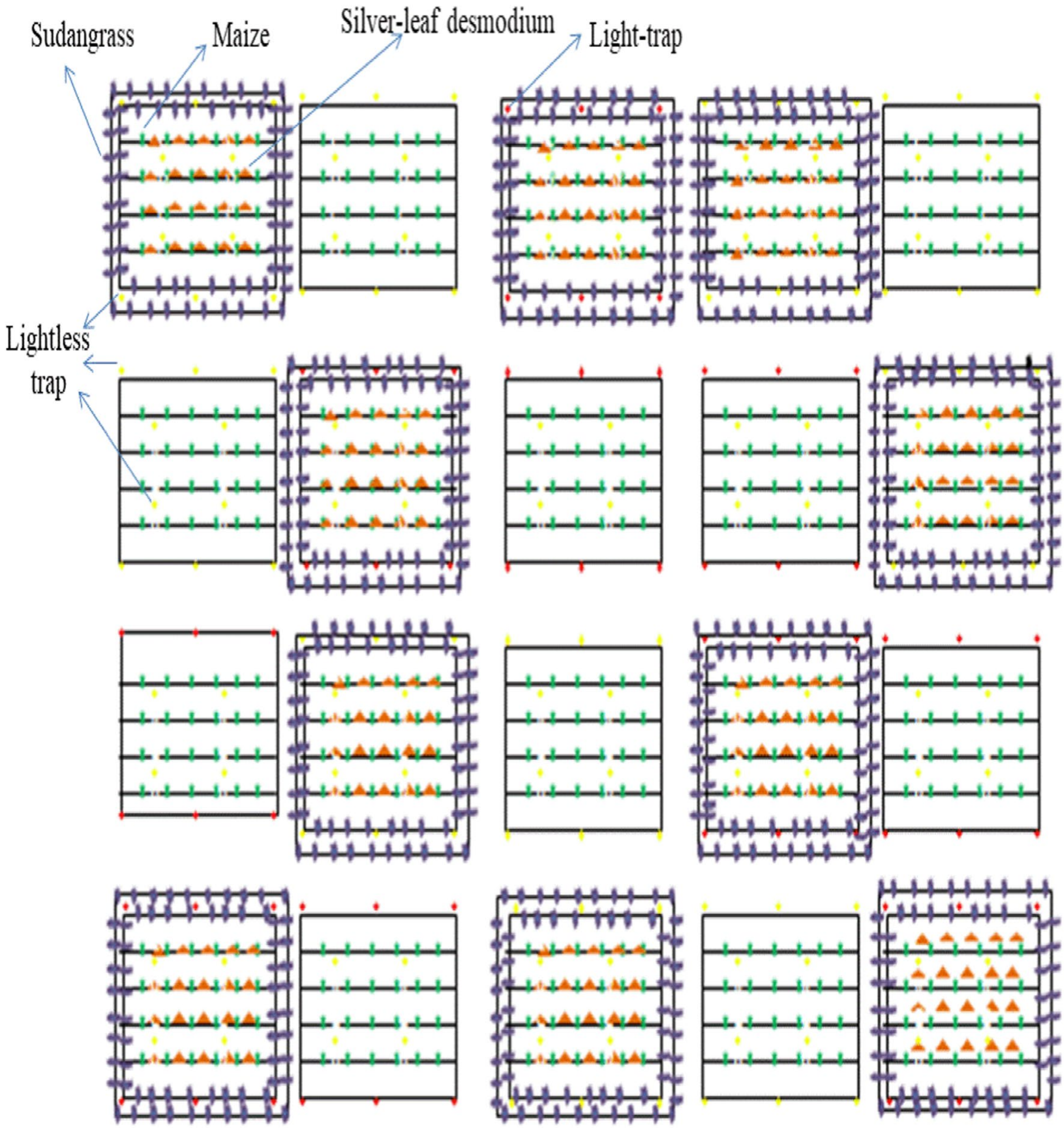

Fig. 1 Layout of treatments

rows with 6 plants per row for a total of 24 plants per plot. Three weeks after planting (after plants have developed two true leaves), six lightless traps were placed at the edges of the plot (i.e. traps were placed outside plots) with a 2 m interval between consecutive light-traps.

Night-time light-trap treated maize plots (Light-trap): Plots were planted with maize seeds the same as described in the monocrop treatment. Three weeks after planting, the plot was applied with six night-time light-traps (d.light) at the edges of the plot (i.e. light-traps were placed outside plots) with a 2 m interval between consecutive light-traps.

Push–pull treated maize plots (Push–pull): Plots were planted with maize seeds the same as described in the monocrop treatment and intercropped with silver leaf desmodium (push-plant) seeds at equidistance between intra-row maize plants. The plot was then surrounded by two rows of Sudangrass (pull-plant) with inter- and intra-row spacing of 0.5 m and 0.3 m, respectively, at 0.5 m away from maize plants at the edge of a plot (plot size of 5 m * 4 m). Three weeks after planting, six lightless traps were placed between the two rows of the pull plants (Sudangrass) with a 2 m interval between consecutive traps. The aim of putting the lightless traps inside the pull plants was for uniformity among the treatments that were not treated with light-traps (assuming that lightless traps do not affect behavior of FAM moths).

Light-trap and push–pull integrated system (Light-push–pull): The same as the push–pull treatment, plots were intercropped by maize and silver-leaf desmodium and surrounded by two rows of Sudangrass (pull-plant) at 0.5 m away from edges of the maize field plot with inter- and intra-row spacing of 0.5 m and 0.3 m, respectively. Three weeks after planting, six night-time light-traps were placed between the two rows of the pull-plants (Sudangrass) with a 2 m interval between consecutive traps.

In addition, to examine the deterrence effect of the treatments on FAW moths, four lightless traps were placed equidistantly inside each plot of all treatments (i.e. traps were placed inside plots). The space between consecutive traps was 2 m. In this case, each trap was placed 2.8 m away from the center of the plot (Fig. 1).

Data collection

Data on different life stages of FAW including the number of adults, larvae and eggs, reduction of the level of FAW larvae and eggs infestation on maize due to different treatments, and proportion of maize plants damaged by FAW larvae were collected from the different treatments as described below.

FAW moths captured on traps under different treatments

The number of FAW moths captured on outside and inside maize plots were counted every 2 weeks during the 2018 and 2019 experiment seasons. Trap count data started two weeks after seedling emergence.

FAW egg and larvae infestation on maize plants

Number of FAW eggs and larvae were counted from six randomly selected maize plants per plot of each treatment every three days and the summation of two weeks of data was used for analysis (data were taken five times within two weeks). To avoid double counting of the same eggs, the counted groups of eggs (moths lay eggs in batches) were marked nearby with a red marker.

FAW eggs and larvae infestation as affected by the different treatments relative to maize monocrop plants

The percent reduction of infestation of FAW eggs and larvae in light-traps, push–pull and light-push–pull plots relative to monocrop plots was determined as follow.

$$\text{Percent reduction of FAW eggs treatment} = \frac{(\text{EC} - \text{ET})}{\text{EC}} * 100$$

where EC refers to the average number of eggs in control (monocrop plots), and ET refers to the average number of eggs in treated maize plots either by light-traps, push–pull or integrated light-trap and push–pull system.

$$\text{Percent reduction of FAW larvae} = \frac{(\text{LC} - \text{LT})}{\text{LC}} * 100$$

where LC refers to the average number of larvae in monocrop (maize monocrop) plots, LT is the average number of larvae in treated maize plots either by light-traps, push–pull or integrated light-trap and push–pull system.

Proportion of plants damaged by FAW larvae

Depending on the growth stage of maize, FAW larvae are found on young leaves, leaf whorls, tassels, or cobs (Goergen et al. 2016). In the current study, damage of FAW larvae on young leaves and leaf whorls during the vegetative growth of all plants in each treatment was assessed non-destructively. During the vegetative phase of the plants, feeding by the FAW larvae results in skeletonized leaves and heavily windowed whorls loaded with larval frass (Goergen et al. 2016). Data were assessed by examining the vegetative parts of each plant for visible larval damage (plants with skeletorized leaves and heavily windowed whorls loaded with larvae or frass), and data which were taken once a week until the end of the experiment and summed to count the total number of plants damaged per plot and were expressed as the percentage of plants damaged per plot.

Data analyses

Collected data were analyzed using MINITAB 17 software package (Minitab 17 Statistical Software 2010). The number of FAW adults caught in traps, the level of infestation by FAW eggs and larvae per plant in maize plants, the percent reduction of FAW eggs and larvae infestation on maize plants due to different treatments, and the proportion of plants damaged by FAW larvae were subjected to Analysis of Variance (ANOVA) after the data were checked for normality. Any significant difference among treatment means was compared using the Tukey–Kramer Multiple Range Test at a 5% alpha level.

Results

FAW moths captured on traps under different treatments

The numbers of FAW moths captured in traps outside maize plots of the four treatments were significantly different during the 2018 and 2019 experiment seasons. Accordingly, a significantly greater number of FAW moths were captured on traps placed outside maize field plots treated with the light-trap and push–pull integrated system than the other treatments during the 2018 (Fig. 2a; ANOVA: $df = 3, 19$: $P < 0.001$) and 2019 (Fig. 2b; ANOVA: $df = 3, 19$; $P < 0.001$) experiment seasons. FAW

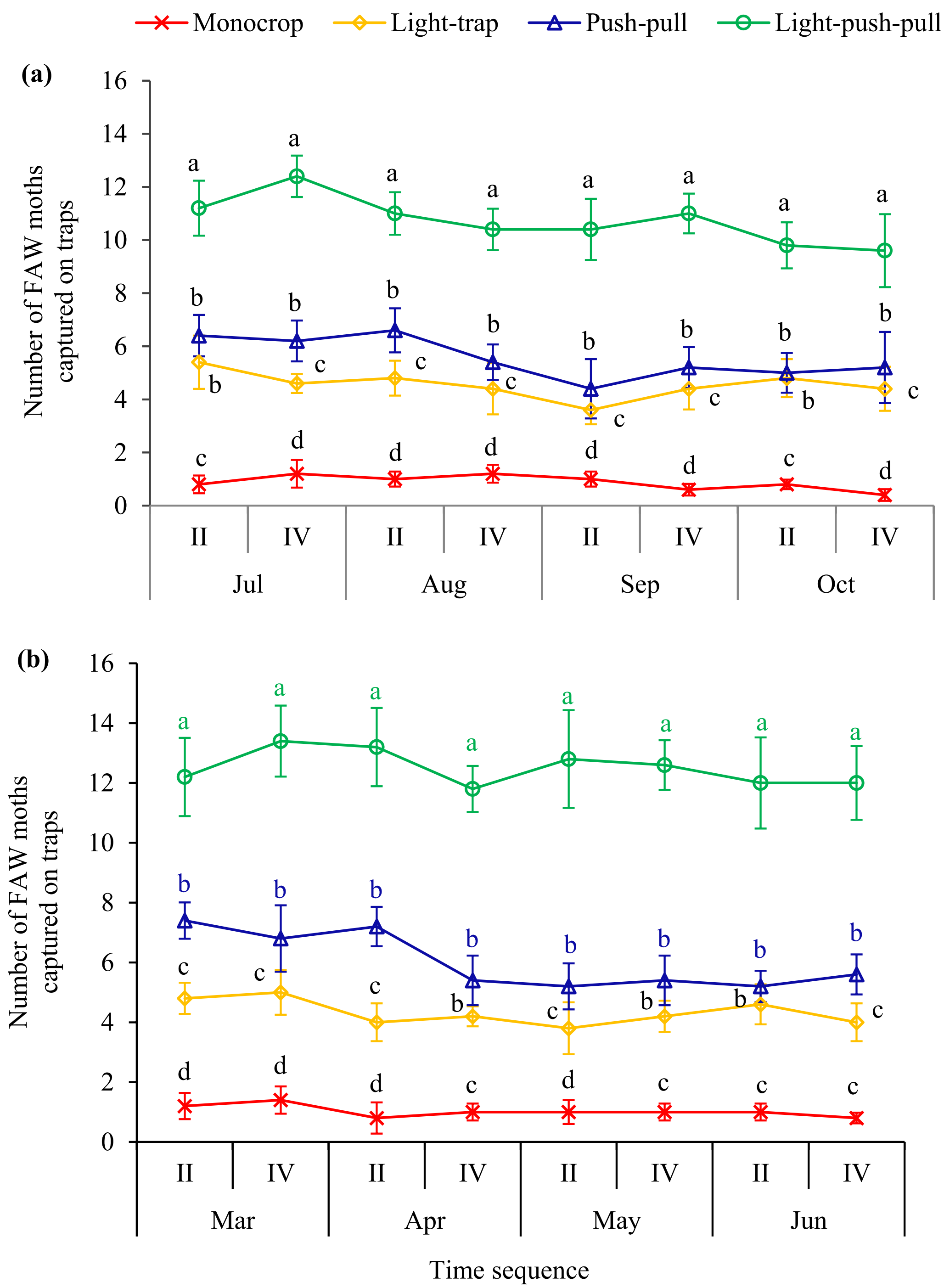

Fig. 2 Number of FAW moths captured on traps outside maize plots when exposed to different treatments during **a** 2018 and **b** 2019 experiment seasons. Means of treatments at a given time period followed by different letters are significantly different. Error bars are standard errors of means; II: second week; IV: fourth week

moths captured on traps placed outside maize field plots treated with light-trap alone and push–pull alone treatments were significantly greater than the monocrop plots (Fig. 2a, b) during the 2018 and 2019 experiment seasons. In addition, FAW moths captured on traps placed outside maize field plots treated with push–pull were significantly greater than FAW moths captured on traps placed outside the light-trap treated maize plots in both experiment seasons except during the second weeks of July and October of 2018 experiment season and during the fourth weeks of April and May and the second week of June of 2019 experiment season in which the number of FAW moths captured were similar between the two treatments. There was no significant effect due to treatment-by-date interaction on the number of FAW moths captured.

The number of FAW moths captured on traps inside maize field plots exposed to different treatments were significantly different in 2018 (Fig. 3a; ANOVA: $df = 3, 19$; $P < 0.001$) and 2019 (Fig. 3b; ANOVA: $df = 3, 19$; $P < 0.001$) experiment seasons. A significantly greater numbers of FAW moths was captured on the monocrop traps placed inside maize field plots than the other treatments followed by light-traps treated and push–pull treated maize field plots, respectively, both in the 2018 and 2019 experiment seasons. The number of FAW moths captured on light-traps and push–pull treated maize plots were significantly greater than the number of FAW moths captured on the light-push–pull treated maize plots both in 2018 and 2019 (experiment seasons except during the second week of 2018 and second weeks of March and April of 2019 experiment seasons in which the push–pull treated maize plots were similar to the light-push–pull treated maize plots in the number of FAW moths captured (Fig. 3a, b). The number of FAW moths captured inside maize plots treated with light-traps were significantly higher relative to the FAW moths captured on push–pull treated maize plots during 2018 and 2019 experiment seasons except during the fourth week of 2018 experiment season in which the number of FAW moths captured were similar (Fig. 3a, b). These indicate that the light-push–pull treatment effectively repelled the entrance of FAW moths to the inside of the maize plots than the other treatments followed by push–pull and light-trap treated maize plots (Fig. 3a, b). There was no significant effect due to treatment-by-date interaction on the number of FAW moths captured.

FAW egg infestation on maize plants when exposed to different treatments

The FAW egg counts on maize plants were significantly different among treatments during the 2018 (Fig. 4a; ANOVA: $df = 3, 19$; $P < 0.0001$) and 2019 (Fig. 4b; ANOVA: $df = 3, 19$; $P < 0.0001$) experiment seasons. A significantly greater numbers of eggs were recorded from maize plants in the monocrop plots followed by the light-trap, push–pull, and light-push–pull treated maize plots in both experiment seasons (Fig. 4a, b). The egg count was also significantly different among maize plots treated with the light-trap, push–pull, and light-push–pull from which the lowest egg count was recorded on maize plots treated with the light-push–pull followed by push–pull and light-trap treatments. There was no significant effect due to treatment-by-date interaction on the number of FAW egg infestation.

FAW larval infestation on maize plants exposed to different treatments

FAW larval infestation on maize plants (number of larvae per plant) was significantly different among treatments during the 2018 (Fig. 5a; ANOVA: $df = 3, 19$, $P < 0.0001$) and 2019 (Fig. 5b; ANOVA: $df = 3, 19$, $P < 0.0001$) experiment seasons. A significantly greater number of larvae was recorded from maize plants in the monocrop compared to all the other treatments both during the 2018 (Fig. 5a; ANOVA: $df = 3, 19$; $P < 0.0001$) and 2019 experiment seasons (Fig. 5b; ANOVA: $df = 3, 19$; ANOVA: $P < 0.0001$) followed by the light-trap and push–pull treated maize plants, respectively. A significantly greater level of FAW larval infestation was recorded on light-trap treated maize plants than push–pull and light-push–pull treated maize plants both during the 2018 and 2019 experiment seasons. FAW larval infestation was significantly greater on the push–pull treated maize plants compared to the light-push–pull treated maize plants except on the second weeks of July and October of 2018 and the second week of March and the fourth week of June of 2019 experiment seasons in which case there was no significant difference between the two treatments. There was no significant effect due to treatment-by-date interaction on the number of FAW larval infestation.

Reduction in FAW eggs and larval infestation from different treatments relative to monocrop plots

The light-push–pull treated maize plots resulted in significantly higher reduction of FAW egg infestation on maize followed by the push–pull and light-trap treated maize plots, respectively, both in the 2018 and 2019 experiment seasons (Fig. 6a; ANOVA: $df = 2, 14$; $P < 0.0001$).

Similarly, the percent reduction in FAW larval infestation on maize plants was significantly higher in light-push–pull treated maize plots followed by push–pull- and light-trap treated maize plots compared to the maize monocrop plots in both experiment seasons (Fig. 6b; ANOVA: $df = 2, 14$; $P < 0.0001$).

Proportion of plants damaged by FAW larvae

The proportion of plants damaged by FAW larvae was significantly different among the treatments both in 2018 (Fig. 7; ANOVA: $df = 3, 19$; $P < 0.001$) and 2019 (Fig. 7; ANOVA: $df = 3, 19$; $P < 0.001$) experiment seasons. In both experiment seasons, light-push–pull treated maize plots showed the lowest proportion of plants damaged by FAW larvae followed by the push–pull and light-trap

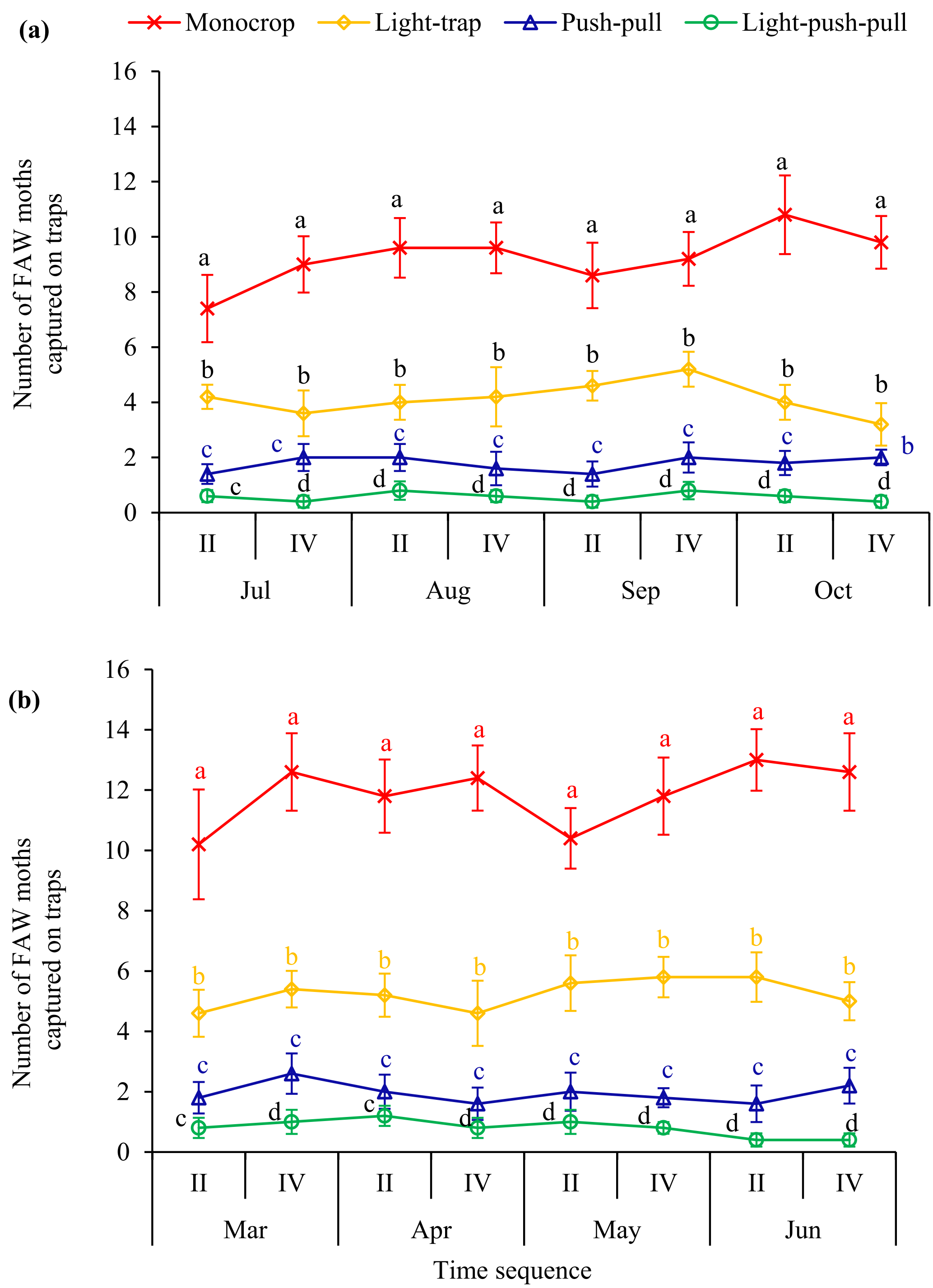

Fig. 3 Number of FAW moths captured on traps inside maize plots when exposed to different treatments during **a** 2018 and **b** 2019 experiment seasons. Means of treatments at a given time period followed by different letters are significantly different. Error bars are standard errors of means; II: second week; IV: fourth week

treated maize plots (Fig. 7). Push–pull and light-trap treated maize plots had significantly lower proportion of plants damaged by FAW larvae comparedthe to monocrop plots during both seasons. The proportion of plants damaged by FAW larvae on the push–pull treated maize plots was significantly lower than light-trap treated maize plots during both experiment seasons (Fig. 7).

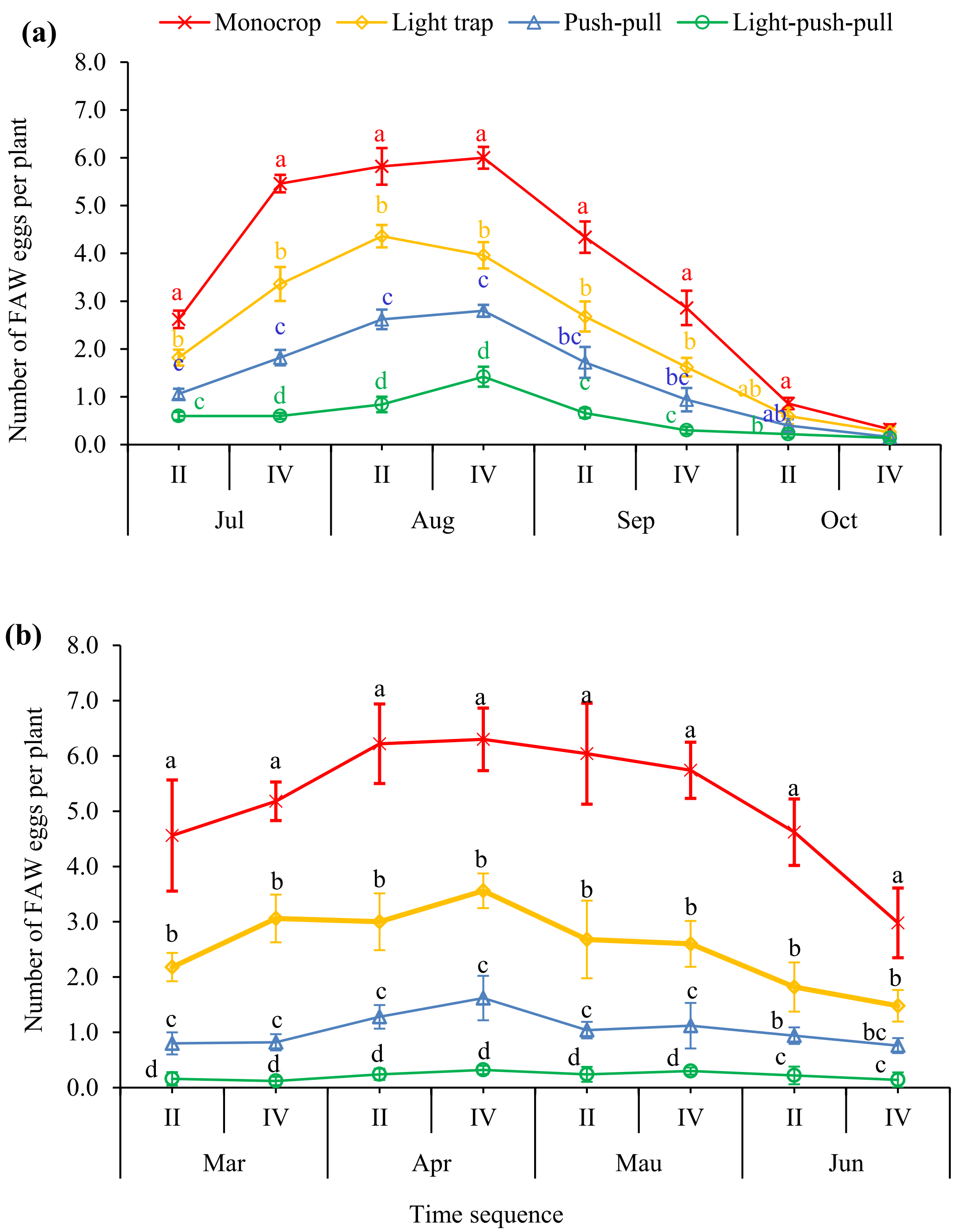

Fig. 4 FAW egg infestation (number of eggs per plant) on maize plants exposed to different treatments during **a** 2018 and **b** 2019 experiment seasons. Means of treatments followed by different letters at a given time period are significantly different. Error bars indicate standard errors; II: second week; IV: fourth week

Discussion

Several studies have reported the effectiveness of the push–pull technology for management of pests (lepidopteran insect pests and Striga) and improvement of soil fertility (such as Midega et al. 2018; Kumela et al. 2019; Midega et al. 2015a; Pickett et al. 2014; Kebede et al. 2018; Khan et al. 2016; Owuor et al. 2018; Mudereri et al. 2019; Murray and Jepson 2019; Mutyambai 2019). It has been reported as an effective and smallholder-farmer-friendly management method of FAW and other lepidopteran species in the sub-Saharan African countries (Midega et al. 2018; Gebreziher and Gebreziher 2020;

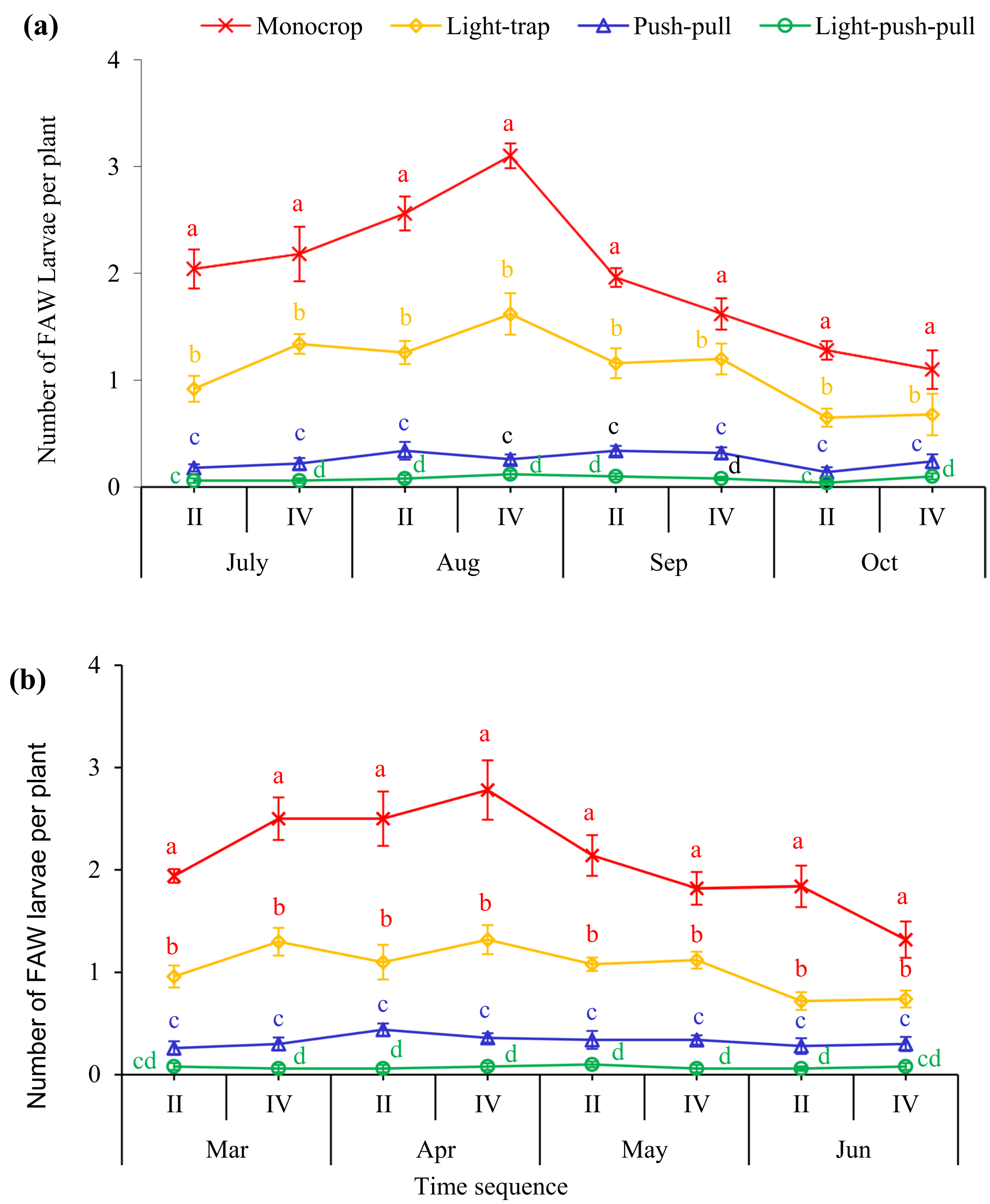

Fig. 5 FAW larval infestation (number of larvae per plant) on maize plants when exposed to different treatments during **a** 2018 and **b** 2019 experiment seasons. Means of treatments followed by different letters at a given time period are significantly different. Error bars indicate standard errors of mean; II: second week; IV: fourth week

Gebreziher 2020a; Mutyambai et al. 2019; Mutyambai et al. 2019; Kansiime et al. 2019). For instance, Hailu et al. (2018) found that maize plots applied with a push–pull system resulted in a significant reduction of FAW, stemborer, and Striga compared to maize monocrop plots and maize intercropped with edible legumes. Similarly, a study in Kenya, Uganda, and Tanzania revealed that push–pull treated maize plots significantly reduced FAW larval infestation and plant damage compared to maize monocrop plots (Midega et al. 2018). Midega et al. (2018) similarly found that the push–pull system resulted in 82.7% reduction in the average number of larvae per plant and 86.7% in plant damage per plot compared to maize monocrop plots.

The findings in the current study proved that different stages of FAW can further be reduced by an integrated approach involving night-time light-traps and the push–pull system. The results of the current study show that

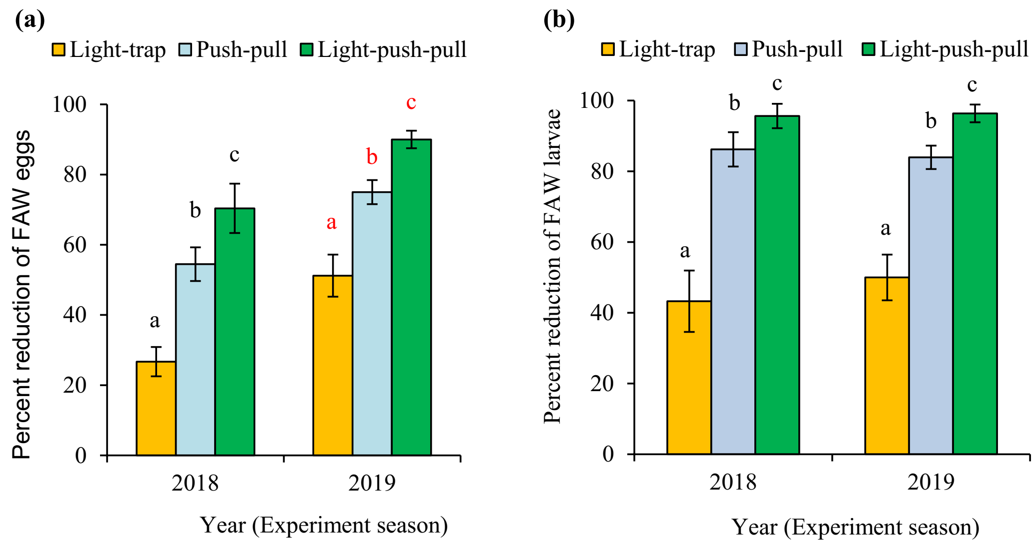

Fig. 6 Comparison of mean proportion of reduction of **a** FAW eggs and **b** FAW larval infestations on maize plants by different treatments relative to maize monocrop plots. Error bars indicate standard errors of the mean; means followed by different letters at a given experiment season are significantly different

integrating light-traps with the push–pull system further enhanced the control of FAW more than the push–pull system alone. The integration of light-traps and push–pull system significantly reduced the number of FAW moths inside maize plots, the level of infestation by FAW eggs and larvae, and the proportion of plants damaged by FAW larvae relative to the push–pull, light-trap and maize monocrop plots both on the rain-fed (2018) and irrigated (2019) experiment seasons.

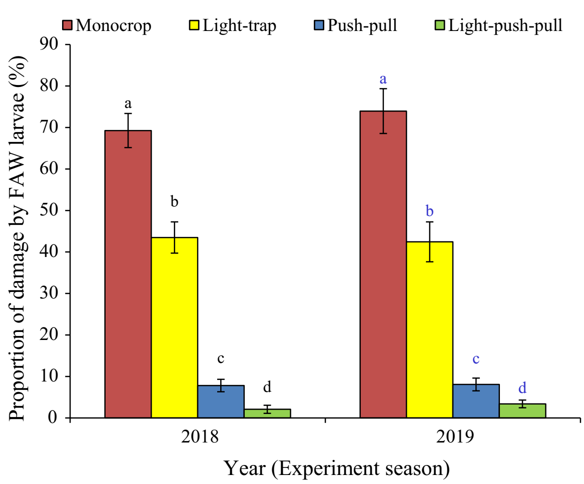

Fig. 7 Proportion of maize plants damaged by FAW larvae when exposed to different treatments. Numbers are the proportion of plants damaged by FAW larvae per plot; error bars indicate standard error of means; means followed by different letters in a given experiment season are significantly different

The lower number of FAW moths inside maize plots treated with the light-push–pull system indicates that moths were attracted to the night-time light traps and those who escaped the light-traps might be repelled by the volatile chemicals emitted from silver-leaf desmodium whereas the chemicals released from the trap crop (Sudangrass) might have resulted in their accumulation outside the maize plot, triggering to oviposit eggs on the trap crop. The enhanced control of FAW by integrating the light-trap and push–pull system might be a result of the combined attraction FAW moths to light and the behavior-modifying chemical cues released from the push–pull system. Previous research findings have reported the attractiveness of light-traps to different lepidopteran moths (Gebreziher and Gebreziher 2020; Jonason et al. 2014; Bhusal and Chapagain 2020), such as FAW given their nocturnal behavior (Gebreziher and Gebreziher 2020; Bhusal and Chapagain 2020; Vilarinho et al. 2011; Meagher et al. 2019). As previously reported, the silver-leaf desmodium releases volatile chemicals that repel female lepidopteran moths (Hailu et al. 2018; Midega et al. 2015a, 2017, 2018; Gebreziher 2020b; Khan et al. 2000, 2006, 2010, 2016; Hassanali et al. 2008; Tamiru and Khan 2017). These chemicals include (*E*)-β-ocimene, (*E*)-4,8-dimethyl-1,3,7-nonatriene, and (1R,4E,9S)-caryophyllene (Midega et al. 2015a; Poveda and Kessler 2012; Pickett et al. 2014; Hassanali et al. 2008; Khan et al. 2010; Tamiru and Khan 2017). On the other hand, pull-plants release chemicals such as (*Z*)-3-hexen-1-ol, octanal, nonanal, naphthalene, 4-allylanisole, eugenol and linalool (Midega et al. 2018, 2017) that attract female moths, triggering them to lay their eggs on leaves of the pull-plants rather than the maize plant (Hailu et al. 2018; Midega et al. 2018; Gebreziher 2020a, 2020b; Khan et al. 2011; Harrison et al. 2019; Pickett et al. 2014). Thus, the underpinning reasons for the enhanced control of FAW in the current study might have resulted from the combined the effects attraction FAW female moths to light and the pushing and pulling effect of the pull–push system.

The integrated light-push–pull approach also resulted in a significant reduction of FAW eggs and larval infestation on maize plants compared to the push–pull or light-traps alone as well as relative to the maize monocrop plots. The underlying mechanism for the reduction of infestation by these consecutive FAW stages might have arisen from the combination of the following mechanisms. First, as the number of FAW moths entering the maize plot becomes restricted as a result of the light-traps and push–pull systems, it is expected that the numbers of eggs and larvae on maize plants would decrease. Second, the chemical cues released from the silver-leaf desmodium (push-plant) might have deterred the FAW female moths from ovipositing their eggs on the target crop (maize). Previous findings reported that chemical cues such as (*E*)-β-ocimene, and (*E*)-4,8-dimethyl-1,3,7-nonatriene released from silver-leaf desmodium are known to repel lepidopteran nocturnal moths such as stem borer (Midega et al. 2018, 2017; Khan et al. 2000; Stenberg et al. 2015). Given their similar nocturnal behavior as that of stemborers it is likely that the chemicals deterred FAW moths from ovipositing their eggs on maize plants. Third, the same chemicals released from the pull-plant might attract the FAW female moths to oviposit their eggs on them instead of maize since the Sudangrass might release more attractive chemical cues compared to maize. Previous findings revealed that trap crops release more attractive chemicals than maize (Midega et al. 2018, 2015a; Khan et al. 2011). However, further studies are needed to elucidate the effects of the chemical cues released from the push–pull system and their integration with night-time light on the behavioral responses of FAW female moths.

The level of FAW larval infestation on maize plants was significantly reduced in the light-push–pull system compared to the push–pull system and light-trap treated maize plots as well as compared to the maize monocrop plots. This might be a result of fewer or no FAW moths entering the maize plots and a reduced number of FAW eggs in the maize plots treated with the light-push–pull system. As reported from previous findings, after the eggs hatch the pull-plants release saps that have toxic or killing effects on the larvae of nocturnal lepidopteran pests (Midega et al. 2018; Khan et al. 2000, 2011). This might be an additional underlying mechanism for the reduction of FAW larvae in the light-push–pull integrated approach. In general, the reduction of FAW larval infestation in the integrated approach might be a result of the reduced FAW moths inside the maize plots, reduced oviposition, and release of toxic chemicals that kill FAW larvae. Yet, further investigation on the effect of chemicals from Sudangrass on the feeding behavior and survival of FAW larvae is recommended for full elucidation.

Several researchers found that utilization of the push–pull system by maize producing smallholder farmers in sub-Saharan Africa has increased the productivity of maize compared to non-user smallholder farmers (Midega et al. 2018, 2015a; Kumela et al. 2019; Khan et al. 2018; Kassie et al. 2018). For instance, Midega et al. (2015a) found that maize yields were 2.5 times higher in push–pull treated maize plots relative to maize monocrop plots. Kassie et al. (2018) also found that the adoption of the push–pull system led to significant increases in maize yield and net income in Kenya, showing its potential benefit in terms of increasing economic surplus. Similarly, Midega et al. (2018) reported that push–pull treated maize plots result in 2.7 times higher maize grain yields compared to maize monocrop plots. Considering these benefits, integrating the push–pull system with night-time light-traps could further increase the yield of maize relative to the push–pull system alone. Yet, further study on the effect of integrating push–pull system and light-traps on the yield of maize and other economic benefits (such as forage, soil fertility improvement, and control of other pests) is needed.

The current finding proved that integrating the push–pull system with other pest monitoring or control mechanisms can further enhance the control of different life stages of FAW. In such an integrated insect behavior-modifying approach, maize fields could be less apparent to FAW moths and the combination of the light-traps and push–pull system may result in effective control of this insect pest. The current findings are expected to contribute to the intensive efforts being made to contain FAW in the sub-Saharan African countries that is affecting several million smallholder farmers involved in maize production.

Conclusion

Since maize constitutes a major stable food and feed source for millions of people and considering its huge economic contribution for smallholder farmers in the sub-Saharan Africa including Ethiopia, controlling FAW is of paramount importance. The push–pull system is considered as an effective and smallholder-farmers-friendly control mechanism for FAW as well as other major maize pests such as various stemborer species and Striga, indicating that this system can provide good control of several maize pests at the same time. From the current study, it can be inferred that integrating the push–pull system with night-time light-traps results in better and more effective control of different life stages of FAW than the push–pull system or light-trap alone. This proves that an integrated approach could be more effective in containing FAW infestations than using the push–pull system as a stand-alone control method. This integrated approach could improve the productivity of maize though further investigation is needed whether significant yield increases can be achieved by this approach. Furthermore, the underlying mechanisms such as the combined effects of light and chemical cues from the push–pull system on the behavioral responses of FAW moths and larvae stage need further investigation.

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Author contributions
Both author (Haftay G. Gebreziher and Fissiha G. Gebreazgaabher) were involved in conceptualization, developing research methodology, data collection, analysis and interpretation. Both authors were a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
Data can be available through a request to the corresponding author.

Declarations

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Not applicable.

Consent for publication
Not applicable.

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