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Effects of Integrating Push-Pull Technology and Maize-Potato Intercropping on the Management of Maize and Potato Insect Pests

Haftay Gebreyesus Gebreziher

haftay.gebreyesus@adu.edu.et

Adigrat University

Simon Zebelo

University of Maryland Eastern Shore

Mehari Gebremichael

Adigrat University

Hagos Abraham

Adigrat University

Senait Tsaedu

Adigrat University

Yohannes Gerezihier Gebremedhin

Adigrat University

Gebremedhin Welu Teklu

Adigrat University

Araya Kahsay Gerezgiher

Adigrat University

Gebrelibanos Gebremariam Gebremedhin

Adigrat University

Tesfay Gidey Bezabh

Adigrat University

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Abstract

Crop diversification through the integration of push–pull technology (PPT) and other agronomic practices, such as intercropping, provides ecological functions, including insect pest management. This study evaluated the effects of integrating maize–potato intercropping and PPT (an integrated approach) on the management of fall armyworm (*Spodoptera frugiperda*), stem borer (*Chilo partellus*) and potato tuber moth (*Phthorimaea operculella*) larvae. The study was conducted in Hatset district, Hawzien, northern Ethiopia. A significantly lower number of *S. frugiperda* and *C. partellus* larvae and a lower level of plant damage were recorded in the maize plots treated with PPT and the integrated approach than in the maize monocropped plots and the maize–potato intercropped plots. A significantly lower number of *P. operculella* larvae and a lower level of plant damage were recorded in the intercropped maize–potato plots than in the monocropped potato plots. Thus, combining maize–potato intercropping with PPT significantly reduced *S. frugiperda* and *C. partellus* larval infestation in maize and *P. operculella* larval infestation in potato. This study revealed that integrating maize–potato intercropping and PPT can be an effective management approach to control *S. frugiperda*, *C. partellus* and *P. operculella* larval infestations, providing a comparative advantage for controlling multiple insect pests in an ecologically diversified cropping system.

1. Background

Agriculture is the center of sustainable development, mainly in developing countries such as Ethiopia, to meet the national food requirements and economy [1], contributing approximately 50% of the GDP, employing 80% of the population, directly supporting 85% of the population, and constituting 80% of the export value [2]. However, the sustainable productivity of the agricultural sector in the country, which is dominated by smallholder farmers, is affected by limiting factors such as existing and newly emerging pests [1], low soil fertility, poor agronomic practices, drought and small landholding [3, 4].

Devising integrated, climate-smart and sustainable good agricultural practices is vital to combat these factors. There are good agricultural practices that utilize the integration of different agronomic practices to combat multiple limiting factors of crop production. Climate-smart push–pull technology (PPT) is among the environmentally friendly agricultural practices involving intercropping main crops with companion plants to control pests (insect pests and striga) [5–7], improve soil fertility [8] and produce livestock fodder [9].

Climate-smart PPTs can be applied to major crops, such as maize and maize-based farms, which are often constrained by pests and low soil fertility [4]. Maize (*Zea mays* L.) and potato (*Solanum tuberosum* L.) are among the major crops produced and constitute major staple food sources for millions of people in Ethiopia [10, 11]. The maize crop is one of the major cereal crops in Ethiopia and is a major staple food and feed source for millions of people in the country [10, 12–16]. It accounts for more than 27% of crop production [4] and is produced in almost all agro-ecologies with both rain-based and irrigation systems,

with smallholder farmers accounting for the largest share of its production. On the other hand, potato is also an important food and cash crop, especially in the high- and middle-altitude areas of Ethiopia [17].

However, the productivity of these crops remains low due to different biotic and abiotic factors [4, 17]. For example, the average maize yield in Ethiopia is 3.24 ton ha^{-1}, which is lower than the world average of 4.5 ton ha^{-1} [18]. This is attributed to both biotic (mainly diseases, weeds, and insect pests) [14] and abiotic (such as low soil fertility and poor agronomic practices) factors, such as inefficient production methods, low soil fertility, drought, and small land holdings [3, 4].

Among the biotic factors, insect pests such as the potato tuber moth (*Phthorimaea operculella* L.) affect potato productivity [17, 19], whereas the fall armyworm (*Spodoptera frugiperda* JE Smith) and different species of stem borers such as *Chilo partellus* Swinhoe predominantly affect maize production and productivity [5, 20, 21].

Climate-smart push-pull technology (PPT) is a novel tool, a low-cost and multipurpose system for integrated pest management, improvement of crop yield, improvement of soil fertility and production of animal fodder. It uses a combination of behavior-modifying stimuli to manipulate the distribution and abundance of insect pests and their natural enemies, striga and the management of soil fertility [5, 8, 21–23]. It involves intercropping target crops such as maize with a repellent plant, such as silver-leaf desmodium, *Desmodium uncinatum* J (Fabales: Fabaceae) (a push-plant), which repels or deters insect pests, and planting an attractive trap plant, such as Sudan grass, *Sorghum sudanense* P (Cyperales: Poaceae) or Napier grass, *Pennisetum purpureum* S (Cyperales: Poaceae) (pull-plants), as a border crop around the intercropped field to attract an insect pest, thus facilitating their accumulation and control [5–7, 21, 24–28].

On the other hand, intercropping maize and potato is a popular planting pattern that can increase land productivity and control insect pests of potato, such as the notorious insect pest *Phthorimaea operculella* [17]. In particular, intercropping potato with maize has been a major pattern widely used in most potato planting [17]. An integrated approach (integrated agronomic practices) involving crop diversification is vital to combat maize and potato insect pests. Therefore, the aim of this project is to evaluate the effects of integrating maize–potato intercropping with climate-smart PPT for insect pest management, with an emphasis on *S. frugiperda*, *C. partellus* and *P. operculella* in Tigray, Northern Ethiopia.

2. Methodology

2.1 Area description

The study was conducted at Hatset Tabia (Tabia: a small administrative unit below the Woreda level), Tigray, northern Ethiopia. The study area is located at an elevation of 2105 m a.s.l. and receives annual rainfall of up to 500 mm year-1 and a temperature range of 18–28°C. Like those in the other districts of

northern Ethiopia, the communities in the study area are dependent on mixed agriculture involving crop production (such as wheat, maize, sorghum, barley, potato, tomato, pepper and others) and livestock production. The farmers in the area produce maize and potato twice a year through rain feed and irrigation. The study was conducted under irrigation conditions from February to June 2025.

2.2 Experimental materials

Maize (*Zea mays* L.; variety: Melkassa-1Q) and potato (*Solanum tuberosum* L.; variety: Belete) were used as the main crops for the study. Maize seeds and potato sprouts were purchased from certified seed producers. Companion crops, including silver-leaf desmodium (*Desmodium uncinatum* J; Fabales: Fabaceae*)* as a push-plant, received from the Ethiopia Biodiversity Institute, and Sudan grass (*Sorghum sudanense* P; Cyperales: Poaceae) as a pull-plant, received from the Gantafeshum Bureau of Agriculture and Natural Resources, were used in the study.

2.3 Treatments and experimental design

The study included five treatments: (1) maize monocropping (maize monocrop plots); (2) potato monocropping (potato monocrop plots); (3) maize–potato intercropped plots; (4) PPT–treated maize plots; and (5) PPT–treated maize–potato intercropped plots. Each treatment was replicated four times in a randomized complete block design. The distance between consecutive plots was 1 m. The treatments used for the study are described below.

Maize monocrop plots

Maize seeds were planted at 0.70 m and 0.30 m inter- and intrarow spacings, respectively, in a 3.5 m by 1.8 m plot and in 5 rows with 6 plants per row for a total of 30 plants per plot.

Potato monocrop plots

potato tubers were planted in a 3.5 m by 1.8 m plot, with each potato tuber planted in a 0.7 m by 0.3 m inter- and intrarow spacing, respectively, in 5 rows with 6 plants per row for a total of 30 plants per plot.

Maize-potato intercropped plots: The maize –potato intercrop plots included two rows of potatoes, with spacing as described for potato monocropping, and three rows of maize, with spacing as described for maize monocropping, which were intercropped in an alternative planting pattern in a 3.5 m × 1.8 m plot. The potato was planted two weeks earlier than the maize was planted.

PPT-treated maize plots

Maize was intercropped with silver-leaf desmodium (push plant) and surrounded by two rows of Sudan grasses (pull plant) 0.5 m away from the edges of the maize plot, with inter- and intrarow spacings of 0.25 m and 0.15 m, respectively.

PPT-treated maize–potato intercropping plots: Maize–potato intercropping was planted (as described for the maize–potato intercropping treatment). Maize within rows was intercropped with silver-leaf

desmodium (push plant). The whole plot was then surrounded by two rows of Sudan grasses (pull plants) 0.5 m away from the edges of the maize plot, with inter- and intrarow spacings of 0.25 m and 0.15 m, respectively.

All the plots were kept free from any chemical insecticide treatment. Uniform agronomic management, such as fertilizer application, watering, and weeding, was applied for all the treatments on the basis of the recommended practices.

2.4 Data collection

2.4.1 *Level of S. frugiperda and C. partellus larval infestation during the vegetative growth stage*

Level of *S. frugiperda* **larval infestation on maize**: The level of *S. frugiperda* larval infestation in each treatment was recorded by counting the number of *S. frugiperda* larvae weekly during the vegetative growth stage.

Level of *C. partellus* **larval infestation on maize**: Similarly, the level of *C. partellus* larval infestation in each treatment was recorded by counting the number of *C. partellus* larvae weekly during the vegetative growth stage.

2.4.2 Levels of P. operculella larval infestation during the vegetative growth stage

The level of *P. operculella* larval infestation in each treatment was recorded by counting the number of larvae weekly during the vegetative growth stage.

2.4.3 *Levels of S. frugiperda, C. partellus and P. operculella larval infestation at harvesting time*

Level of plant damage (damage incidence) caused by *S. frugiperda* **and/or** *C. partellus* **larvae**: Damage caused by *S. frugiperda* and *C. partellus* larvae on young leaves and leaf whorls during vegetative growth was assessed nondestructively as described in Tanyi et al [29] except for the scale used in this study, which ranged from 1–5 (where 1 = very low or no visible sign of damage and 5 = completely damaged). During the vegetative plant growth stage, feeding by the larvae results in skeletonized leaves and heavily windowed whorls loaded with larval frass Gebreziher & Gebreziher [30]. Therefore, damage caused by larvae was assessed weekly by examining the vegetative parts for visible larval damage. The labels used for plant damage include the following:

- Very low or no visible sign of damage to plants = 1
- Low level of damage with little sign of damage = 2
- Moderate level of damage that can cause moderate yield loss = 3

- High level of damage (plants still grow, but damage can cause reduced plant growth and significant yield loss) = 4
- Completely damaged: entirely injured plant with no more ability to produce yield = 5

The degree of damage to plants caused by *S. frugiperda* or *C. partellus* was expressed as the level of damage to the plants in each plot.

Level of plant damage (damage incidence) caused by *P. operculella*: Damage caused by *P. operculella* larvae on potato leaves during vegetative growth was assessed nondestructively via labels 1 to 5. Plots of each treatment were examined for the presence of mines weekly until harvest. Damage caused by larvae was assessed by examining the vegetative parts of each plant for visible larval damage, and the data were expressed as the level of damage to the plants per plot.

2.4.4 Levels of plant damage caused by S. frugiperda, C. partellus and P. operculella larvae

2.5 Data analysis

The collected data were analyzed via the MINITAB 17 software package and IBM SPSS 20. The levels of infestation by *S. frugiperda*, *C. partellus* and *P. operculella* larvae per plant and the levels of plants damaged by *S. frugiperda*, *C. partellus* or *P. operculella* larvae were subjected to two-way analysis of variance (ANOVA). Any significant differences among the treatment means were compared via the least significance difference (LSD) test at the 5% significance level.

3. Results and discussion

3.1 Effects of integrating maize–potato intercropping and climate-smart PPT on the levels of *S. frugiperda* and *C. partellus* larval infestation

3.1.1 *S. frugiperda and C. partellus larval infestation during the vegetative stage*

The results revealed that the number of *S. frugiperda* larvae infestations on maize plants was highly significantly different among the treatments (Fig. 2 and Table 1). Compared with those in the other treatments, a significantly greater number of *S. frugiperda* larvae were recorded in the maize monocrop plots, followed by the maize–potato intercropped plots. A significantly lower number of *S. frugiperda* larvae was recorded in potato monocrop plots, maize–potato intercropped plots treated with PPT and maize plots treated with PPT.

Similarly, the number of *C. partellus* larvae infestations on maize plants was highly significantly different among the treatments (Fig. 3 and Table 1). Compared with those in the other treatments, a highly significantly greater number of *C. partellus* larvae were recorded in the maize monocrop plots, followed by the maize–potato intercropped plots. A significantly lower number of *C. partellus* larvae was recorded in potato monocrop plots, maize–potato intercropped plots treated with PPT and maize plots treated with PPT.

Table 1
Levels of *S. frugiperda and C. partellus* larval infestation among the different treatments expressed as the mean number of larvae per plot

Treatments	**Mean number of larval infestation**			
	***S. frugiperda* larvae during vegetative stage**	***S. frugiperda* larvae inside cobs at harvest**	***C. partellus* larvae during vegetative stage**	***C. partellus* larvae inside cobs at harvest**
M	8.23 ^{d}	8.15 ^{c}	4.280 ^{b}	4.76 ^{b}
P	0.09 ^{a}	-	0.49 ^{a}	-
MP	5.73 ^{c}	4.75^{b}	3.98 ^{b}	3.75 ^{b}
MPP	1.14 ^{b}	1.00^{a}	0.64 ^{a}	1.25 ^{a}
MPPP	0.73 ^{ab}	0.75^{a}	0.50 ^{a}	0.70 ^{a}
F value	112.21***	54.23***	32.2***	16.40***

Means followed by different letters are significantly different. M: maize monocrop; P: potato monocrop plots; MP: maize-potato intercropped plots; MPP: maize plots treated with push –pull technology; MPPP: maize-potato intercropped plots treated with push –pull technology

Table 2
Source of variation in the level of *S. frugiperda* larval infestation among the different treatments during vegetative growth

Sources of variation	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Intercept	2155.69	1	2155.69	453.06	0.000
Trt	2286.57	4	571.64	112.21	0.000
Time	714.72	10	71.47	32.22	0.000
Blk	14.25	3	4.75	0.98	0.436
Trt * Time	701.06	40	17.53	9.05	0.000
Trt * Blk	55.13	12	4.59	1.37	0.079
Time * Blk	66.59	30	2.22	1.15	0.297
Trt * Time * Blk	227.10	117	1.94	40.00	0.126

Trt: Treatment; Blk: Block

The number of *S. frugiperda* and *C. partellus* larvae was also highly significantly affected by time and by the interaction between treatment and time (Figs. 2, 3 and Tables 2, 3). The number of *S. frugiperda* and

C. partellus larvae varied over time, as shown in Figs. 2 and 3, respectively. However, blocking had no significant effect on the number of *S. frugiperda* or *C. partellus* larvae (Table 1).

Table 3
Source of variation in the level of *C. partellus* larval infestation among the different treatments during vegetative growth

Sources of variation	Sum of Squares	df	Mean Square	F	Sig.
Intercept	928.04	1	928.04	218.66	0.000
Trt	794.57	4	198.64	112.17	0.000
Time	250.63	10	25.06	15.42	0.000
Blk	12.72	3	4.24	2.95	0.129
Trt * Time	248.47	40	6.21	3.17	0.000
Trt * Blk	21.25	12	1.77	0.90	0.548
Time * Blk	48.80	30	1.63	0.83	0.718
Trt * Time * Blk	230.00	117	1.97	28.00	0.216
Trt: Treatment; Blk: Block					

3.1.2 *S. frugiperda and C. partellus larvae infestation at harvest*
The results revealed that the number of *S. frugiperda* and *C. partellus* larvae infestations on the maize cobs was highly significantly different among the treatments (Table 1) at harvest. Compared with those in the other treatments, a significantly greater number of *S. frugiperda* and *C. partellus* larvae were recorded in the maize monocrop plots, followed by the maize–potato intercropped plots. A significantly lower number of *S. frugiperda* and *C. partellus* larvae were recorded in the maize–potato intercropped plots treated with PPT than in the maize plots treated with PPT. No significant difference in the number of *S. frugiperda* larvae in the maize cobs was recorded between the maize-potato intercropped plots treated with PPT and the PPT-treated maize plots. Similarly, the number of *C. partellus* larvae infestations on the maize cobs was highly significantly different among the treatments (Table 1). Compared with those in the other treatments, a significantly greater number of *C. partellus* larvae were recorded from maize plants in monocrops, followed by maize–potato intercropping. A significantly lower number of *C. partellus* larvae was recorded in the maize–potato intercropped plots treated with PPT and the maize plants treated with PPT. No significant difference in the number of *C. partellus* larvae in the maize cobs was recorded between the maize-potato intercropped plots treated with PPT and the maize plots treated with PPT.

Several studies have reported that climate-smart push–pull technology reduces infestations of maize insect pests such as *S. frugiperda* and *C. partellus* larvae [4–6, 20, 22, 31, 32]. For example, Hailu et al [20]

reported that, compared with maize monocrop plots and maize intercropped with edible legumes, maize plots treated with climate-smart push–pull technology resulted in a significant reduction in *S. frugiperda* and *C. partellus* larvae. Similarly, a study in Ethiopia by Gebreziher & Gebreazgaabher [6] reported that, compared with maize monocrop plots, climate-smart push–pull technology-treated maize plots significantly reduced *S. frugiperda* larval infestation. Another study in Kenya, Uganda, and Tanzania revealed that climate-smart push–pull technology-treated maize plots reduced *S. frugiperda* larval infestation [5]. In another study, PPT performed best in reducing *C. partellus*, *S. frugiperda*, and striga infestations in all the phenological stages of maize [20]. A study by Hailu et al [20] also reported that, compared with monocropped maize, intercropping of maize with leguminous crops resulted in a significant reduction in *C. partellus* and *S. frugiperda*, especially in the early growth phases of maize up to tasseling. The current study revealed that maize plots treated with push–pull technology and maize–potato intercropped plots treated with push–pull technology significantly reduced *S. frugiperda* and *C. partellus* larval infestations compared with those in maize monocrop plots and maize–potato intercropped plots.

3.2 Effects of integrating maize–potato intercropping and climate-smart PPT on *P. operculella* larval infestation

3.2.1 P. operculella larval infestation during the vegetative growth stage

The results revealed that the number of *P. operculella* larvae infestations during vegetative growth was highly significantly different among the treatments (Fig. 4 and Table 4). A significantly greater number of *P. operculella* larvae were recorded from potato monocrop plots than from the other treatments. A significantly lower number of *P. operculella* larvae was recorded in maize monocrop plots, maize plants treated with PPT and maize–potato intercropped plots treated with PPT than in potato monocrop plots and maize–potato intercropped plots.

Table 4
Levels of potato tuber moth larvae infestation among the different treatments

Treatments	Average number of potato tuber moth larvae per plot	
	Number of *P. operculella* larvae during vegetative stage	**Number of *P. operculella* larvae in tubers at harvest**
M	0.21[a]	-
P	4.79 [c]	5.00
MP	1.16 [b]	1.75
MPP	0.155 [a]	-
MPPP	0.136 [a]	0.50
F value	225.55***	10.94**

*Means followed by different letters are significantly different. *** very highly significant; ** highly significant; ns: nonsignificant. M: maize monocrop plots; P: potato monocrop plots; MP: maize –potato intercropped plots; MPP: maize plots treated with push –pull technology; MPPP: maize –potato intercropped plots treated with push –pull technology*

Table 5
Source of variation in the level of *P. operculella* larval infestation among different treatments during vegetative growth

Sources of variation	Sum of Squares	df	Mean Square	F	Sig.
Intercept	358.62	1	358.62	293.73	0.000
Trt	669.06	4	167.27	225.55	0.000
Time	73.79	10	7.38	6.08	0.000
Blk	3.66	3	1.22	1.28	.340
Trt * Time	192.94	40	4.82	4.82	0.000
Trt * Blk	8.90	12	.742	.74	.709
Time * Blk	36.40	30	1.21	1.21	.232
Trt * Time * Blk	117.17	117	1.00	1.20	.521

The number of *P. operculella* larvae during vegetative growth was also significantly affected by time and by the interaction between treatment and time (Fig. 5 and Table 5). The number of potato tuber moth larvae varied over time, as shown in Fig. 3.

3.2.2 P. operculella larval infestation of potato tubers at harvest

The results revealed that the number of *P. operculella* larvae infestations on potato tubers at harvest significantly differed among the treatments (Fig. 5). A significantly greater number of *P. operculella* larvae were recorded on potato tubers from potato monocrops, followed by those from maize–potato intercropping, than on those from maize–potato intercropping plants treated with PPT. Compared with the control plants, the maize–potato intercropping plants treated with PPT recorded significantly fewer *P. operculella* larvae.

Previous findings have indicated that intercropping reduces insect pest infestations on crops [17, 34–39]. For instance, a study in Malawi revealed that the incidence of sweet potato weevil was significantly lower in intercropped systems involving sweet potato and pigeonpea than in monocropped systems [37]. It is often stated that pests are less damaging in fields with a mixture of crops than in fields with a single crop, also known as monocultures. This idea is based in part on the assumption that a given pest will find fewer acceptable hosts to feed or lay eggs on in a more diverse field [38].

The maize plant is a nonhost plant for *P. operculella* [17], which is unsuitable for the insect. Previous studies reported that maize–potato intercropping has various advantages, including improving land use efficiency [40] and reducing potato pests [17, 41]. For instance, Singh et al [41] reported that maize–potato intercropping reduces the incidence and rate of disease development of bacterial wilt (*Pseudomonas solanacearum*) and Rhizoctonia (*Rhizoctonia solani*) in potato crops. Ya-qiang et al [17] reported that the infestation of *P. operculella* larvae was significantly lower in maize–potato intercropped plots than in potato monocrop plots. A study in Egypt revealed that intercropping potato (*S. tuberosum*) with onion (*Allium cepa* L.) significantly reduced potato plant infestation with whitefly and aphids (*Myzus persicae*) [35]. The results of the present study revealed that integrating maize-potato intercropping with PPT significantly reduced *P. operculella* larval infestation in potato both at the vegetative stage and in tubers, which is more efficient than maize-potato intercropping. These findings indicate that integrating maize–potato intercropping with PPT, which is characterized by its diverse crop types, has greater efficiency for *P. operculella* management than does maize–potato intercropping.

3.3 Effects of integrating maize–potato intercropping and climate-smart PPT on the level of damage to plants caused by insect pests

3.3.1 Levels of damage to plants caused by S. frugiperda and C. partellus among the different treatments

The proportions of damage caused by *S. frugiperda* and *C. partellus* were highly significantly different among the treatments (Table 3: df = 4, 3, 19; F = 348.88; $P < 0.0001$). A significantly greater level of damage to maize by *S. frugiperda* and *C. partellus* larvae was recorded from the maize monocrops and the maize–potato intercropping system than from the other treatments. A significantly lower level of damage to maize by *S. frugiperda* and *C. partellus* larvae was recorded in maize–potato intercropping

plants treated with PPT and maize plants treated with PPT. No damage to potato plants caused by *S. frugiperda* or *C. partellus* larvae was recorded. No significant difference in the level of damage to maize plants caused by *S. frugiperda* or *C. partellus* larvae was recorded between maize-potato intercropping plants treated with PPT and maize plants treated with PPT.

Table 6
Levels of damage to plants caused by *S. frugiperda* and *C. partellus* larvae among the different treatments

Treatments	**Level of plant damage by larvae**	
	By *S. frugiperda*	**By *C. partellus***
M	3.00 [b]	2.76 [b]
P	1.00 [a]	1.00 [a]
MP	2.48 [b]	2.59 [b]
MPP	1.28 [a]	1.23 [a]
MPPP	1.16 [a]	1.12 [a]
F value	348.88***	274.65***

The level of damage was as follows: 1.00: no sign of damage; (1.00–2.00]: low level of damage; (2–3]: moderate damage; (3–4]: high level of damage; and (4–5]: entire injury. Means followed by different letters are significantly different. ns: not significant. M: maize monocrop plots; P: potato monocrop plots; MP: maize–potato intercropped plots; MPP: maize plots treated with push–pull technology; MPPP: maize–potato intercropped plots treated with push–pull technology

Several studies have reported that PPT reduces the proportion of damage caused by *S. frugiperda* and *C. partellus* larvae on maize compared with that caused by maize monocropping [22, 30, 33, 43]. A study in twelve districts of Kenya reported that PPT treated maize plots significantly reduced plant damage caused by *C. partellus* compared to maize monocrop plots [22]. Similarly, a study in Kenya reported that maize leaf damage caused by *C. partellus* was significantly lower in push-pull-treated maize plots than in maize monocrop plots [43]. Field studies in northern Ethiopia revealed that the proportion of maize plants damaged by *S. frugiperda* larvae was significantly lower in PPT-treated maize plots than in maize monocrop plots [6, 15]. Studies in Ghana, Kenya, Tanzania, Uganda, and Zambia similarly indicated a notable decrease in *S. frugiperda* infestation and damage compared with monocrops, with an overall median reduction of 46.4% in *S. frugiperda* damage to maize among all studies and countries involved [5].The results of the present study indicate that PPT-treated maize plots and PPT-treated maize-potato intercropped plots recorded lower levels of damage caused by *S. frugiperda* and *C. partellus* than maize monocrop and maize-potato intercropped plots did. However, the PPT-treated maize–potato intercropping system significantly reduced potato tuber moth larval infestation. Therefore, integrating PPT and maize–potato intercropping has a comparative advantage in controlling more insect pests,

including *S. frugiperda*, *C. partellus*, and *P. operculella*, in an ecologically diversified climate–smart cropping system.

3.3.2 Levels of damage to plants caused by P. operculella larvae among the different treatments

a. Vegetative stage

The proportion of damage caused by *P. operculella* was highly significantly different among the treatments (Table 6: df = 4, 3, 19; F = 107.29; $P < 0.0001$). A significantly lower level of damage caused by *P. operculella* larvae was recorded in maize–potato intercropping plants treated with PPT followed by maize-potato intercropping. A significantly higher level of damage caused by *P. operculella* larvae was recorded in potato monocrops. No significant difference in the level of damage to potato plants caused by *P. operculella* was recorded between maize-potato intercropping plants treated with PPT and maize-potato intercropping. No damage to the maize monocrops and maize plants treated with PPT was recorded.

Table 7
Levels of plants damaged by potato tuber moth larvae in response to different treatments

Treatments	**Level of plant damage by *P. operculella* larvae at vegetative stage**
M	1.00 [a]
P	2.65 [b]
MP	1.24 [a]
MPP	1.00 [a]
MPPP	1.15 [a]
F value	107.29***
Means followed by different letters are significantly different. M: maize monocrop; P: potato monocrop plots; MP: maize-potato intercropped plots; MPP: maize plots treated with push –pull technology; MPPP: maize-potato intercropped plots treated with push –pull technology	

b. *P. operculella larval damage at harvest*

The result shows that the percentage of potato tubers with signs of potato tuber moth larval damage was significantly higher in the potato monocrop plots, followed by maize-potato intercropped plots (Fig. 5; $P < 0.05$). Ya-qiang et al [17] reported that potato intercropped with maize reduced adult and larval populations and reduced damage from *P. operculella* by enhancing the number of parasitoids and the level of parasitism.

4. Summary and conclusion

The current study revealed that the approach of integrating maize–potato intercropping with PPT reduces the infestation of maize by *S. frugiperda* and *C. partellus* and potato by potato tuber moth larvae. The integrated approach reduced the level of *S. frugiperda* and *C. partellus* larval infestation on maize both during the vegetative stage and on cobs at harvest and simultaneously reduced *P. operculella* larval infestation on potato leaves and tubers. Therefore, this integrated approach provides an ecologically sound solution for the management of maize and potato insect pests.

The peculiarity of this study lies in its integrated approach to managing multiple species of insect pests and thus preventing damage to a diverse valuable cropping system involving maize, potato, and economically and ecologically important companion crops. The results of the present study suggest that integrating maize–potato intercropping with PPT is an effective and sustainable management approach for controlling *S. frugiperda*, *C. partellus*, and *P. operculella* larval infestations, providing a comparative advantage for controlling multiple insect pests in ecologically diverse cropping systems. Given that the integrated approach can easily be adapted by smallholder farmers, we recommend that integrating maize–potato intercropping and PPT could be an economically and ecologically sound cropping system for maize– and potato–producing areas to prevent pest problems and crop damage.

However, further studies are needed to investigate the interactions among different trophic levels (diverse crop plants, insect pests, and natural enemies), and further investigations are needed to elucidate the ecological and chemical interactions in diversified cropping systems. In addition, further studies on the effects of diverse cropping systems on crop yield, the abundance of natural enemies, and soil fertility improvement are imperative.

Declarations

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Conflicts of Interest:

The authors declare no competing interests.

Author Contribution

All authors have made contribution to the conception of the work and study design. Haftay Gebreyesus Gebreziher, Mehari Gebremichael and Hagos Abraham made the acquisition and formal analysis of the study. All authors contributed to the interpretation of data. Haftay Gebreyesus Gebreziher, Senait Tsaedu and Yohannes Gereziher Gebremedhin prepared all the figures in the manuscript. Haftay Gebreyesus Gebreziher, Mehari Gebremichael and Senait Tsaedu wrote the main manuscript text. All authors reviewed the manuscript. Simon Zebelo has contributed to funding acquisition for article processing charge (if any). All authors have approved the submitted manuscript and agreed to be personally accountable for author's own contributions and ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved are appropriately investigated, resolved, and the resolution documented in literature.

Acknowledgement

We are very thankful to Adigrat University for funding (Grant Registration ID: AGU/CAES/MS/01/2016) the fieldwork of this project. We also acknowledge the Gantafeshum Bureau of Agriculture and Natural Resources for providing Sudan grass seeds and the Ethiopia Biodiversity Institute for supplying silverleaf desmodium seeds. Any opinions, findings, conclusions, or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect the views of the funder. The University of Maryland Eastern Shore will fund the Article Processing Charge (if any) for the publication of the manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

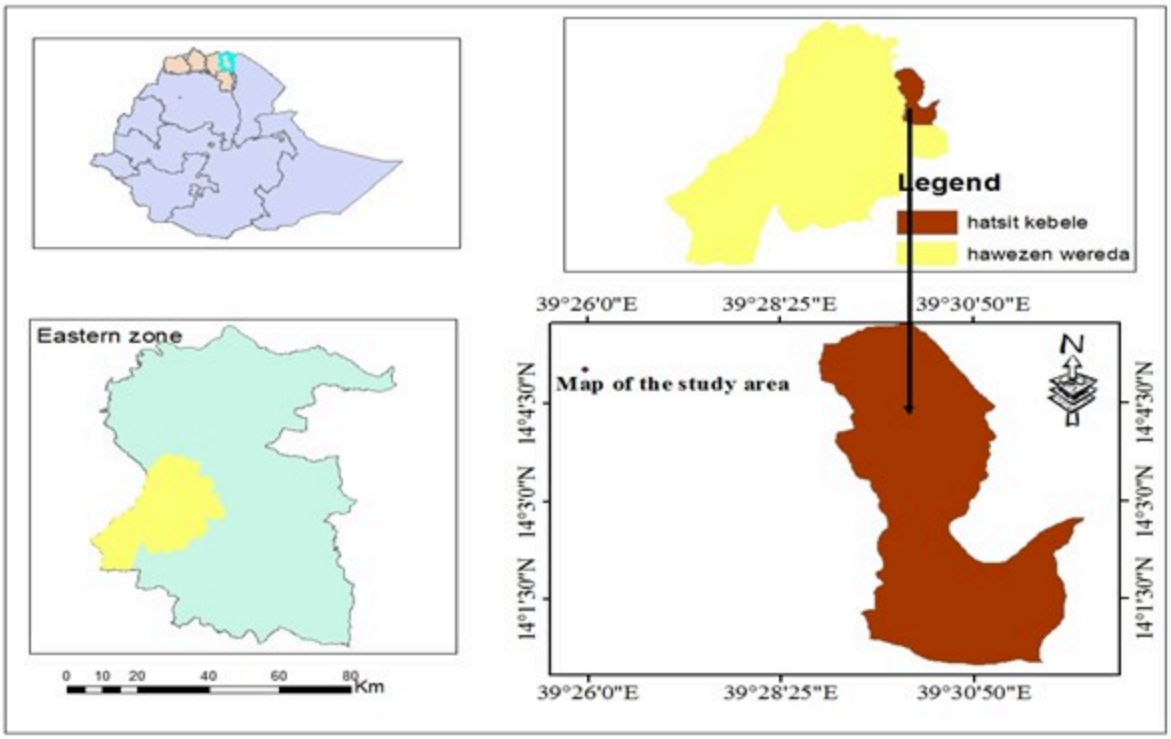


Figure 1

A map showing the Hatset district where the study was conducted

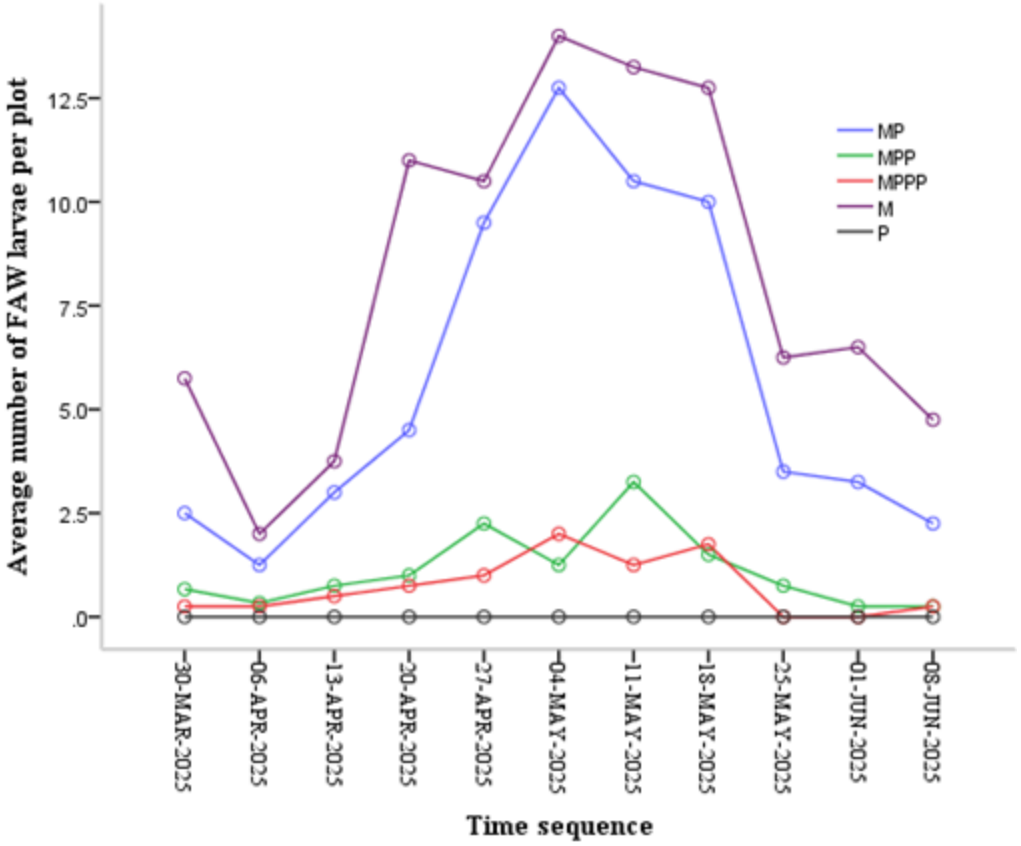


Figure 2

Trends of *S. frugiperda* larval infestation among the different treatments during the study period. Trt: treatment; Blk: block; M: maize monocrop plots; P: potato monocrop plots; MP: maize–potatointercropped plots; MPP: maize plots treated with push–pull technology; MPPP: maize–potato intercropped plots treated with push–pulltechnology

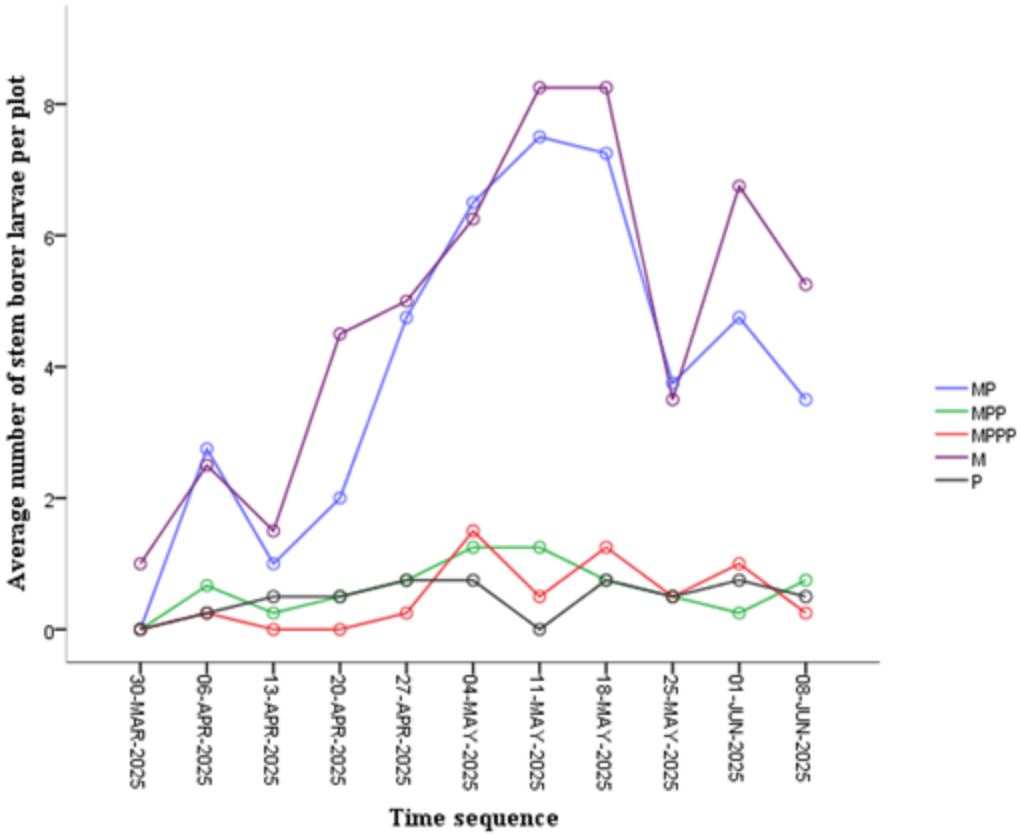


Figure 3

Trends of *C. partellus* larval infestation among the different treatments during the study period. Trt: treatment; Blk: block; M: maize monocrop plots; P: potato monocrop plots; MP: maize–potatointercropped plots; MPP: maize plots treated with push–pull technology; MPPP: maize–potato intercropped plots treated with push–pulltechnology

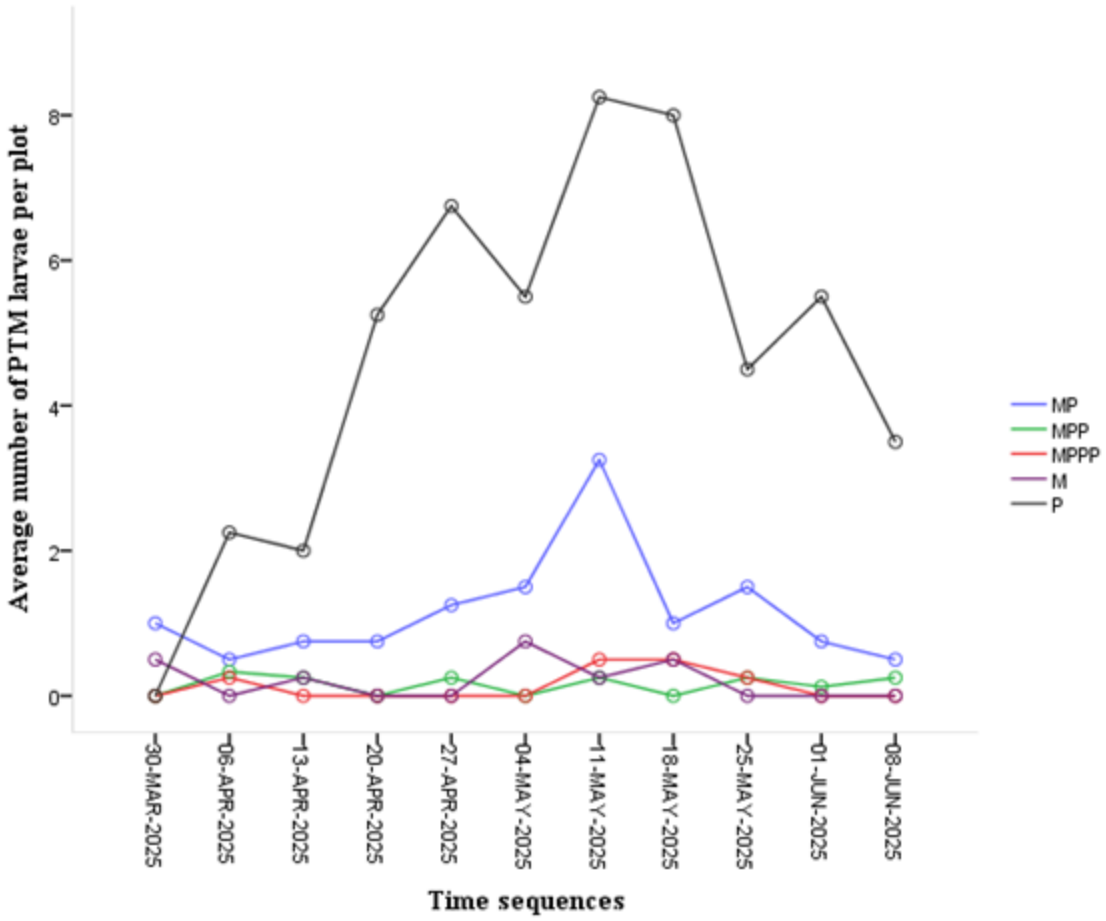


Figure 4

Trends of *P. operculella* larvalinfestation among different treatments and time intervals. M: maize monocrop plots; P: potato monocrop plots; MP: maize–potatointercropped plots; MPP: maize plots treated with push–pull technology; MPPP: maize–potato intercropped plots treated with push–pulltechnology)

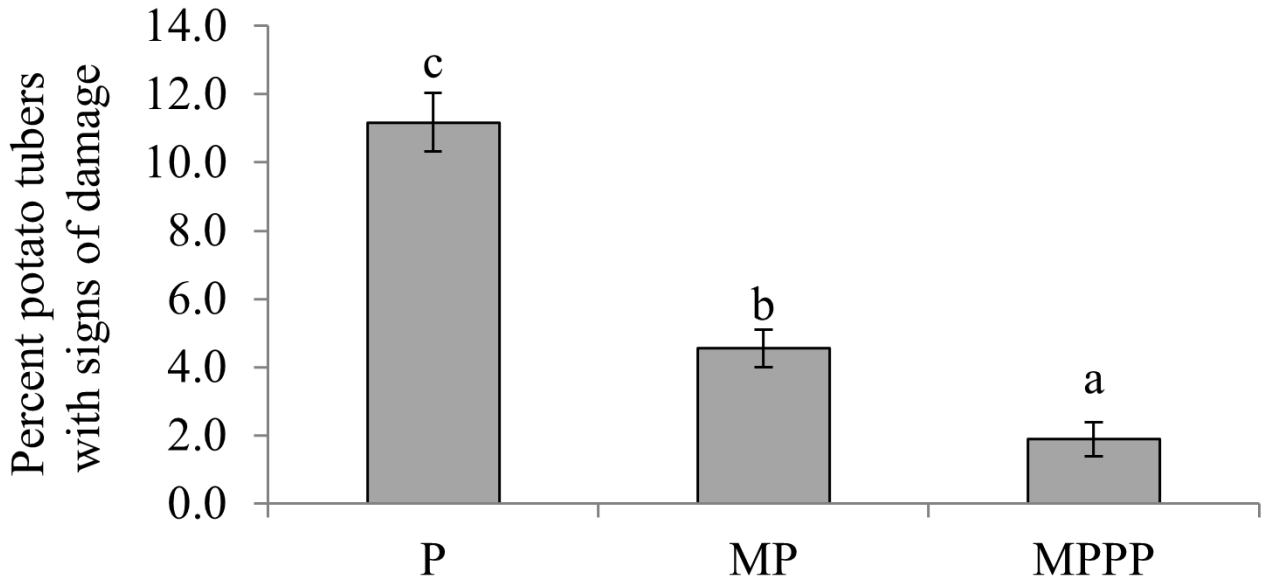


Figure 5

Percent of potato tubers with signs of damage by *P. operculella* . Means followed by different letters are significantly different at $P < 0.05$. P: potato monocrop plots; MP: Maize-potato intercropped plots; MPPP: Maize-potato intercropping treate