Journal of Crop Health (2025)77:40
https://doi.org/10.1007/s10343-024-01107-3

RESEARCH

An Intensified Cereal Push-Pull System Reduces Pest Infestation and Confers Yield Advantages in High-Value Vegetables

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Received: 28 November 2024 / Accepted: 31 December 2024

Abstract
Crop diversification is associated with ecosystem services that can improve yield. We integrated tomatoes and kales within the cereal push-pull technology (PPT), to form the vegetable integrated push-pull (VIPP), and explored the influence of these cropping systems on pest and disease management, and subsequent yield of the vegetables. Aphids and diamondback moths (DBM), the major pests in kale production, together with grasshoppers were consistently lower in the VIPP plots. Low incidences and damage by leafminers, whiteflies and fruitflies on tomatoes were observed in VIPP plots compared to plots of tomato intercropped with maize (control). The severity of black rot and leaf curl on kales and leaf spots on tomatoes were less in VIPP compared to control. We recorded good quality and high yield of tomato and kale grown in VIPP plots rather than control plots. We demonstrate that spatial crop diversification such as integrating vegetables such as kale and tomato in a push-pull system can boost yield and maintain crop integrity.

Keywords Agroecology · Crop diversification · Ecosystem multifunctionality · Nutrition-sensitive agriculture · Plant-insect interactions · Sustainable intensification · Vegetable integrated push-pull

Introduction

The intensification of conventional agriculture is associated with simplified agroecosystems and biodiversity loss. Of major concern is how the reduced biodiversity leads to the loss of key ecosystem services including pest and disease regulation (Tooker and Frank 2012; Chidawanyika et al. 2023), soil fertility and nutrient cycling (Sun et al. 2022; Liu et al. 2024; Ortega et al. 2024), weed management (Midega et al. 2017; Cheruiyot et al. 2021), and moisture conservation (Hu et al. 2017). In turn, the emanating challenges lead to a vicious cycle that is characterised by overreliance on external outputs such as pesticides, inorganic fertilisers, and herbicides to support crop productivity but without biodiversity restoration. For resource-poor farmers, such a production model is unsustainable due to the scarcity of inputs and competing needs for capital investment. Thus, there have been growing calls for alternative modes of production to meet desirable crop, environmental and socioeconomic outcomes through sustainable intensification (Tilman et al. 2011; Tscharntke et al. 2012; Struik and Kuyper 2017; Weltin and Hüttel 2023).

Sustainable intensification, defined as a *process or system where agricultural yields are increased without adverse environmental impact and the conversion of additional non-agricultural land* (Pretty and Bharucha 2014) has broad dimensions where resource use efficiency, whether economic, environmental or social is at the core (Struik and Kuyper 2017). It can partly be achieved through crop diversification by both temporal (rotation) and spatial (intercropping) means (Struik and Kuyper 2017; Tooker and Frank 2012). Literature is now replete with studies showing the advantages of such crop diversification through both bottom-up and top-down factors (Tooker and Frank 2012; Chidawanyika et al. 2020). Belowground, intercropping can enhance microbial activity (Adan et al. 2024; Jalloh et al. 2024) and improve both nutrient cycling (Drinkwater et al. 2021) and crop protection through overexpression of anti-

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Published online: 30 January 2025

herbivore metabolites that aid crop protection (Lang et al. 2024; Bass et al. 2024).

Aboveground, a diversified intercropping system suppresses pest infestations as specialist herbivorous insects tend to favour where there are larger patches of host plants (Stephens and Myers 2012). In what is now regarded as the resource concentration hypothesis, the basis of pest suppression is due to how crop diversity through intercropping impedes host location and migration among specialist insect herbivores (Grez and Gonzalez 1995). Other studies have argued that crop diversification avails more resources for insect diversity, including pest natural enemies (Brandmeier et al. 2021; Rakotomalala et al. 2023), leading to increased parasitism (Khan et al. 1997).

Originally developed to control Lepidopteran pests in African smallholder cereal cropping systems, the push pull technology (PPT) is a companion cropping method where maize or sorghum are intercrops with leguminous plants of the genus Desmodium [Fabaceae] whilst surrounded by Napier grass (*Pennisetum purpureum*) or those of the Brachiaria sp. [all Poaceae] (Cheruiyot et al. 2021, 2022) The Desmodium in the intercrops serve as the push factor by repelling pests (Cheruiyot et al. 2021; Odermatt et al. 2024) whilst attracting natural enemies (Sobhy et al. 2022). The surrounding grasses provide the pull factor by luring pests away from the crop for oviposition whilst arresting larval development (Chidawanyika et al. 2014; Cheruiyot et al. 2021). Together, the companion plants provide crop protection against pests (Midega et al. 2018) in addition to other ecosystem services including suppression of parasitic weeds (Hooper et al. 2015; Midega et al. 2017), soil nitrogen fixation and improved organic content and phosphorous content in the soil (Drinkwater et al. 2021).

Other than pests, diseases also negatively impact the productivity of vegetables. In agricultural ecosystems, there has been recent renewed interest in biodiversity to abate plant diseases. Previous studies have demonstrated how crop diversification can contribute to mitigating pests, weeds and diseases or their influence on natural enemies (Estrada-Carmona et al. 2022; Tobisch et al. 2023). However, evidence of spatial crop diversification to mitigate plant diseases remains scant even though diversified polycultures are generally thought to limit plant diseases (Smith et al. 2015; Wang et al. 2021).

Apart from pest and disease control, sustainable intensification of cropping systems offers opportunities for improving nutritional diversity (Chidawanyika et al. 2023). This is particularly important in sub-Saharan Africa where crop production is largely dominated by cereals (de Graaff et al. 2011; Noort et al. 2022). Hence, we recently integrated vegetables and edible legumes within the PPT to form the vegetable integrated push pull (VIPP). In this current study, we investigated how integrating kales and tomatoes within the VIPP can influence pests and diseases as well as the productivity of these vegetables. We hypothesised that the vegetables will be protected by the insect behavioural manipulation of the PPT together with the resource-based population dynamics of plant-herbivore interactions. We also hypothesised that disease incidences will be lower, given that herbivore damage acts as a predisposing factor for pathogen infection, leading to yield increment.

Materials and Methods

Study Area

The field experiments were conducted at the International Centre of Insect Physiology and Ecology (*icipe*), Thomas Odhiambo Campus, Mbita Point, Kenya (0°25′S, 34°12′E). The experiment was undertaken during the short rain seasons from October to December in 2020 and 2021, as well as during the long rain seasons from March to May and June to August in 2020. This region is characterized by a semi-arid climate, experiencing rainfall patterns that are also endured by smallholder farmers in the region (1933 mm p.a). Mbita Point is situated along the shores of Lake Victoria, which may influence its microclimate. The area typically experiences two main rainy seasons: the long rains from March to May and the short rains from October to December and soils are predominantly vertisol.

Plot Layout

We established a split-plot design of Push-Pull Technology (maize + silverleaf desmodium *Desmodium uncinatum* + Brachiaria around the plot) and control (sole maize) (both 28 × 15 m). At two weeks post seedling emergence, two vegetable types—kales (Collards variety), and tomatoes (Riogrand variety) were planted in both the VIPP and control plots alternating with maize (WH 505 variety) in 5.25 × 5.25 m subplots that were replicated 4 times for the two treatments. The inter- and intra-row spacing between maize was 75 cm and 30 cm, respectively, while desmodium was planted at an inter-row spacing of 75 cm. Kales and tomatoes were planted with an intra-row spacing of 30 cm (Fig. 1).

Pest and Disease Infestation Levels and Severity of Damage

Data collection commenced two weeks post planting of vegetables and continued weekly until the 7th week, concluding with the final harvest. A randomized sampling method was employed by selecting 20 plants from the middle rows of vegetables while excluding border plants. To minimize

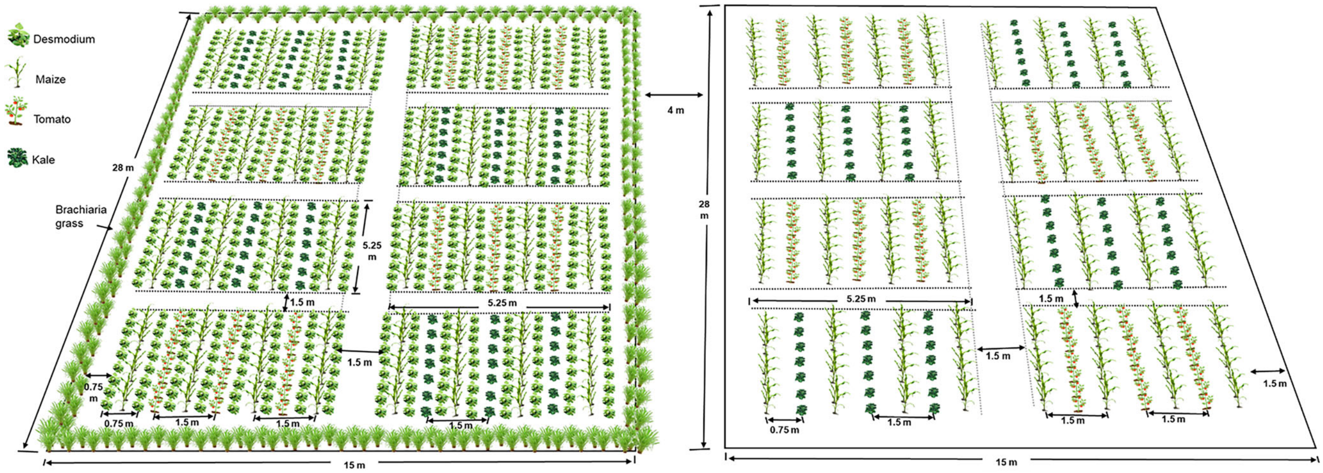

Fig. 1 Overview of experimental layout for vegetable integrated push-pull (VIPP) and control plots cultivated with kales, tomatoes and maize crops

bias, 5 plants were chosen from either side of the middle rows, totaling 20 plants per sampling plot. Pest populations were monitored by inspecting individual plants within each plot. For each plant, the species and abundance of each pest were recorded. Pest damage and disease severity was concurrently assessed by visual inspection.

A 7-point Likert scale (Dvorak et al. 2021) was used to quantify the severity of pest and disease damage, where each level represents the extent of damage observed on the plants: 0 indicating no damage (clean), 1 for very low damage, 2 for low damage, 3 for moderate damage, 4 for high damage, 5 for very high damage, and 6 for complete plant death. In both seasons, pest damage and disease ratings commenced 2 weeks after germination and continued weekly over a 4-week period.

Yield and Quality Assessment in Kales and Tomatoes

Harvesting was done weekly where yield and quality were determined from the same plants where crop health was assessed. The harvested leaves were sorted into 3 distinct batches: the first batch included healthy leaves and those exhibiting low to moderate damage, categorized as consumable; whilst the third batch consisted of severely damaged and diseased leaves, which were classified as non-marketable (rejected). During the quality assessment, a 5-member panel of local farmers was invited to categorise the vegetables after each harvest. Thereafter, the leaves were counted and weighed to determine the yield for each treatment.

Data Analysis

The data for all the surveyed parameters were pooled according to seasons; short rain seasons (October to December 2020 and October to December 2021) and short rain seasons (June to August 2020 and March to May 2021). Pest and disease damage (ratings) and incidences of kales and tomatoes were subjected to a generalized linear model (GLM) in R statistical software (R Core Team 2023).

The disease severity was converted into proportion. The area under disease progress curve (AUDPC) was computed for disease severity following Jeger and Viljanen-Rollinson (2001):

$$AUDPC = \sum_{i=1}^{n-1} \left(\frac{y_i + y_{i-1}}{2}\right)(t_{i+1} - t_i)$$

where:

$n =$ total number of observations,
$y_i =$ proportion disease severity observed on kales or tomatoes at the i^{th} observation, and
$t =$ time (expressed as weeks) at the i^{th} observation.

The computed values of AUDPC for each disease type were subjected to a two-way analysis of variance. In these analyses, seasons and treatments were fixed factors. *Post hoc* analyses were performed using Tukey's HSD (Honestly Significance Difference) test and the significance level was set at $\alpha = 0.05$.

Results

Pest Incidences and Damage Ratings On Kales and Tomatoes

VIPP significantly influenced the incidences of aphids ($\chi^2 = 49.85$, $p < 0.001$), diamondback moth (DBM) ($\chi^2 = 25.56$,

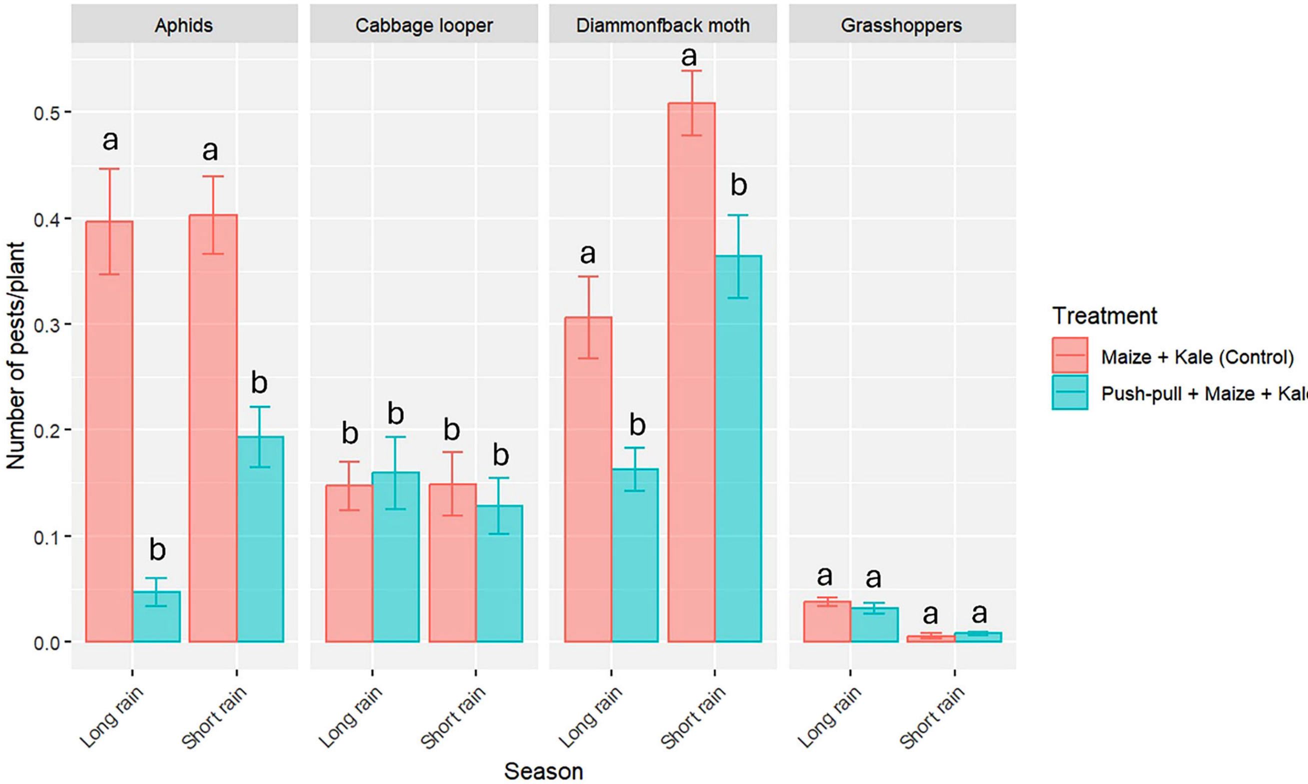

Fig. 2 Incidence of insect pests on kales grown in push-pull (VIPP) and control plots in two cropping seasons (*Bars* represent the means. *Different letters* above the error bars denote significant differences between treatments)

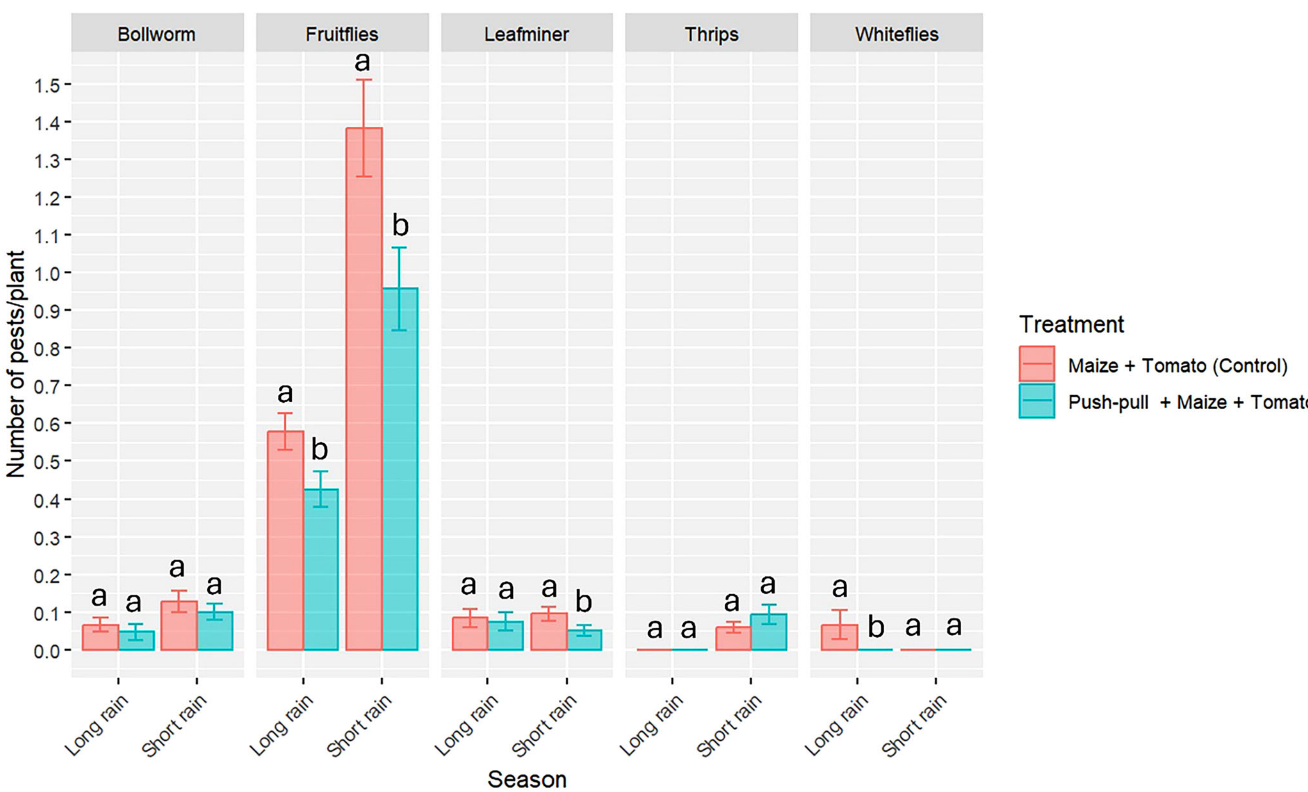

Fig. 3 Incidence of insect pests on tomatoes grown in push-pull (VIPP) and control plots in two cropping seasons (*Different letters* above the error bars denote significant differences)

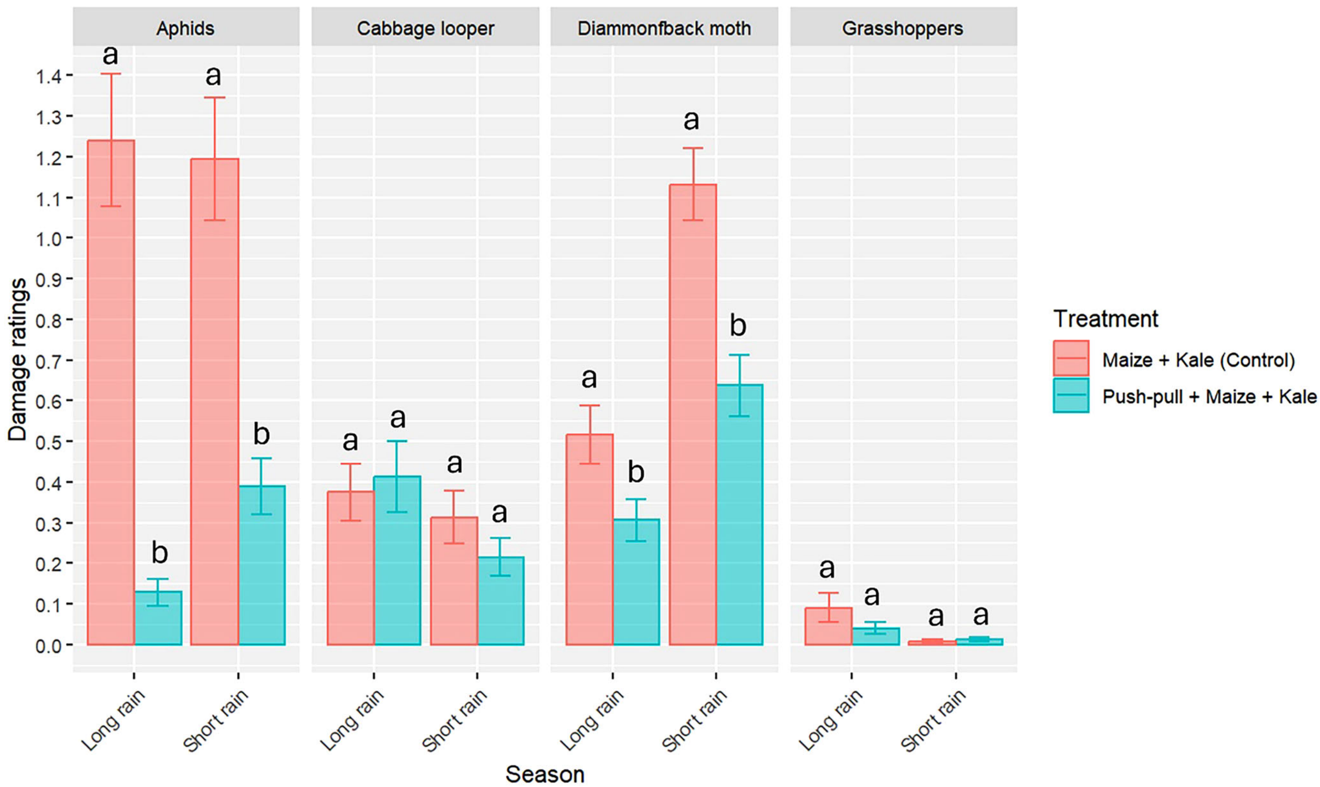

Fig. 4 Insect pests' damage ratings observed on kales grown in push-pull (VIPP) and control plots in two cropping seasons (*Different letters* above the error bars denote significant differences among treatments)

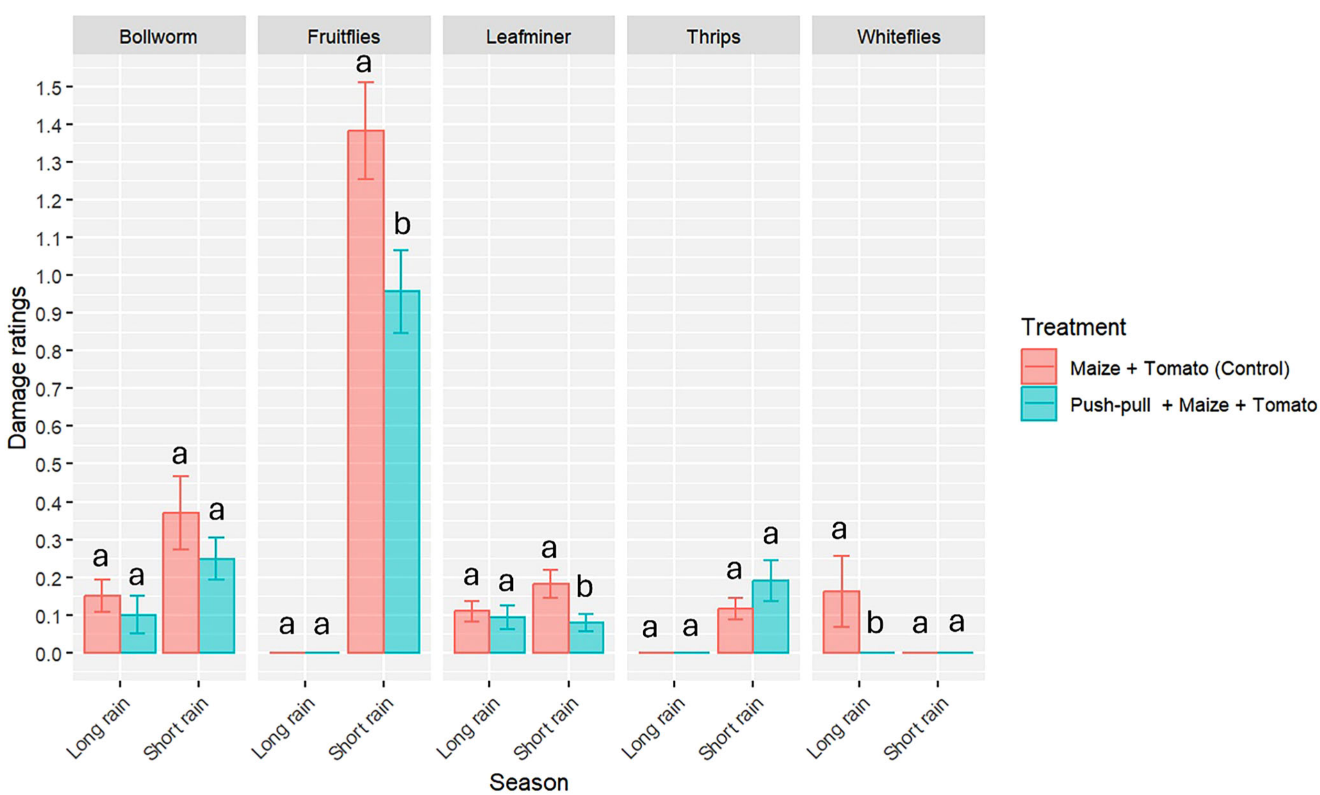

Fig. 5 Insect pests' damage ratings observed on tomatoes grown in push-pull (VIPP) and control plots in two cropping seasons (*Different letters* above the error bars denote significant differences between treatments)

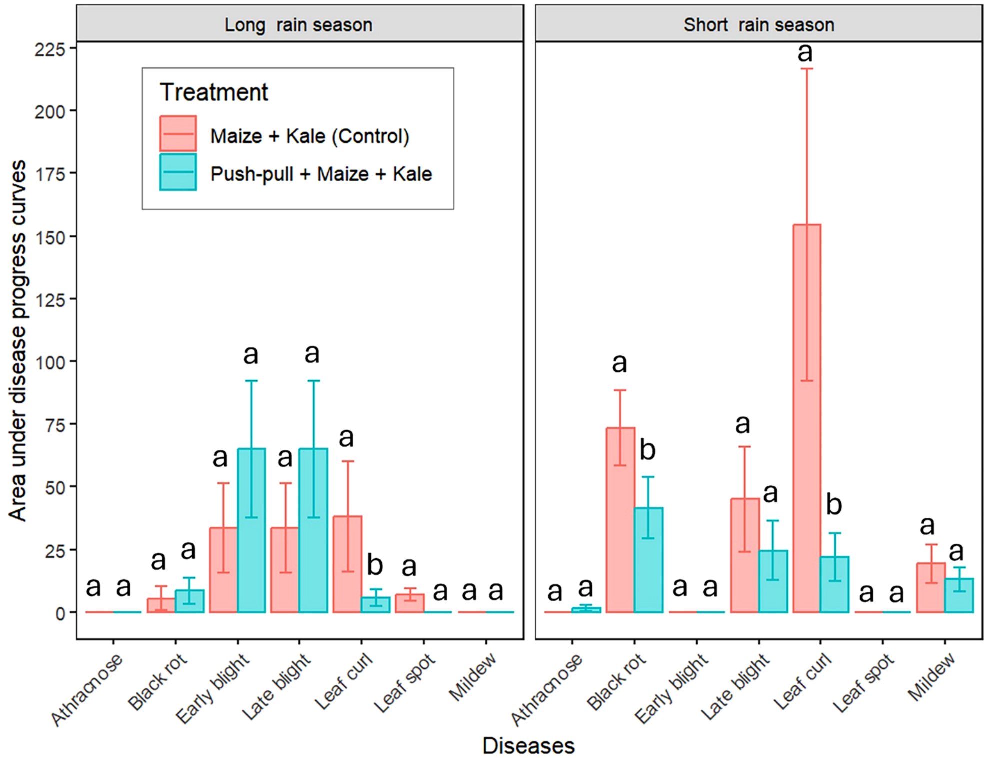

Fig. 6 Area under disease progress curves for disease severity caused by different diseases recorded on kales cultivated in push-pull (VIPP) and control plots in two cropping seasons (*Different letters* above the error bars denote significant differences between treatments)

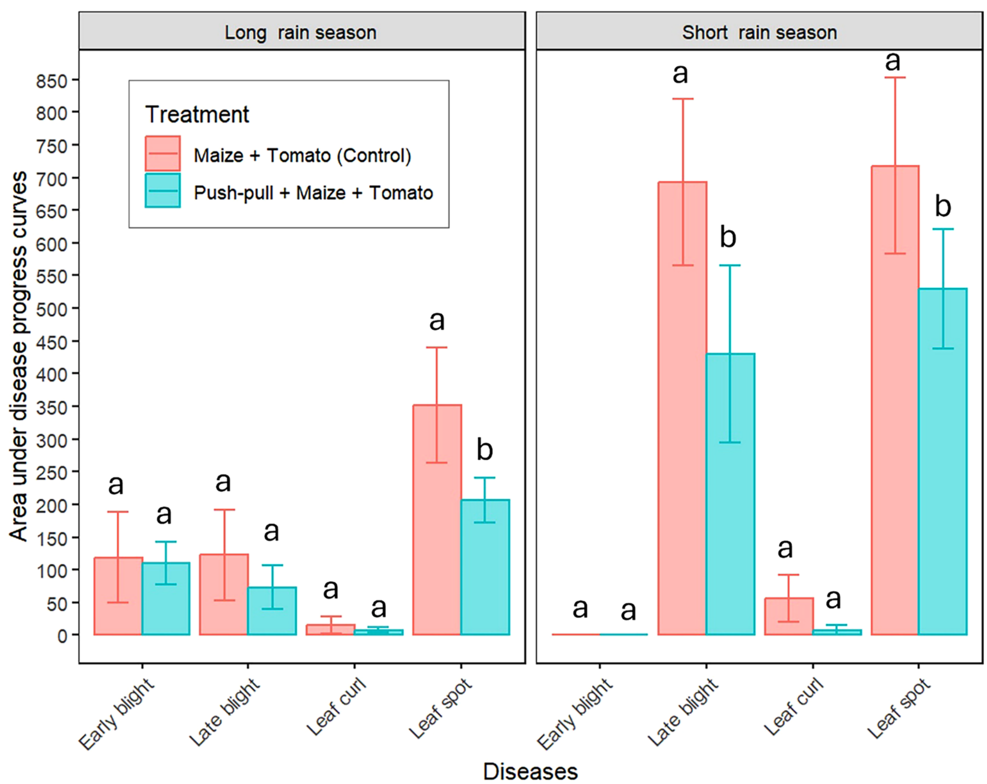

Fig. 7 Area under disease progress curves for disease severity caused by different diseases recorded on tomatoes cultivated in push-pull (VIPP) and control plots in two cropping seasons (*Different letters* above the error bars denote significant differences between treatments)

$p<0.001$), and grasshoppers ($\chi^2=11.83$, $p<0.001$) but not cabbage looper ($\chi^2=0.25$, $p=0.61$) in kales. Only the incidences of DBM and grasshopper varied between the seasons ($\chi^2=25.56$, $p<0.001$, and $\chi^2=11.83$, $p<0.001$, respectively). However, there were no significant interactions between treatments and seasons. Similarly, the severity of damage followed similar trends in line with the pest infestation levels (Supplementary Table S1). Overall, the numbers

Table 1 Statistical summary of generalized linear models for yield parameters of kales

Parameters	Independent variables	χ^2	Df	*p*-value
Number of marketable leaves	Season	25.51	1	**< 0.001**
	Treatment	31.44	1	**< 0.001**
	Weeks after transplanting	5.77	3	0.12
	Season × Treatment	0.09	1	0.76
Number of non-marketable leaves	Season	1.02	1	0.31
	Treatment	54.09	1	**< 0.001**
	Weeks after transplanting	6.99	3	0.072
	Season × Treatment	4.29	1	**0.038**
Weight of marketable leaves	Season	27.44	1	**< 0.001**
	Treatment	87.21	1	**< 0.001**
	Weeks after transplanting	23.26	3	**< 0.001**
	Season × Treatment	0.23	1	0.63
Weight of non-marketable leaves	Season	0.36	1	0.54
	Treatment	52.95	1	**< 0.001**
	Weeks after transplanting	5.37	3	0.15
	Season × Treatment	2.08	1	0.15

The treatment consisted of vegetable integrated push-pull (VIPP) and control plots where experiments were conducted during long and short rain seasons

Yield data were assessed weekly at physiological maturity

of aphids and DBM together with the severity of damage were consistently lower in VIPP plots compared to control plots (maize + kale). However, the incidence (Figs. 2 and 3) and damage (Figs. 4 and 5) levels of cabbage loopers and grasshoppers were not affected by treatments.

In tomatoes, the VIPP significantly influenced infestations by leafminers *Tuta absoluta* ($\chi^2 = 3.05$, $p = 0.004$), whiteflies ($\chi^2 = 5.94$, $p = 0.014$) and fruit flies ($\chi^2 = 9.94$, $p = 0.023$) but not thrips ($\chi^2 = 1.43$, $p = 0.23$) and bollworms ($\chi^2 = 0.92$, $p = 0.33$). There was seasonal variation in the incidences of thrips, bollworms, whiteflies and fruit flies ($p < 0.001$). Only incidences of bollworm and whiteflies were significantly influenced by the interactions of treatments and seasons. The same trends were followed in the damage ratings (Supplementary Table S2).

Low incidences of and damage by leafminers, whiteflies and fruit flies on tomatoes were observed in push-pull plots compared to plots of tomato as a sole crop. No significant variations of the incidences of and damage by thrips and bollworms were recorded between the two treatments (Figs. 4 and 5).

Disease Severity On Kales and Tomatoes

In kales, early and late blight, black rot, leaf curl and leaf spot were observed during long rain season. While in the short rain season, late blight, black rot, leaf curl, mildew and anthracnose were observed (Fig. 6). Unlike other diseases observed on kales, the AUDPC for black rot and leaf curl showed significant variations between treatments (black rot: $F = 4.39$, $p = 0.044$, leaf curl: $F = 6.16$, $p = 0.018$) and seasons (black rot: $F = 22.17$, $p < 0.001$, leaf curl: $F = 4.11$, $p = 0.048$).

Early and late blight, leaf curl and leaf spot were the diseases that were observed on tomatoes (Fig. 7). High severity of late blight and leaf spot were observed in short rain season compared to the long rain season (late blight: $F = 19.56$, $p < 0.001$, leaf spot: $F = 11.39$, $p = 0.004$). Tomatoes in control plots had higher severity of leaf spot compared to tomatoes grown in push-pull plots during long rain season ($F = 9.61$, $p = 0.021$). The AUDPCs for the other diseases were not statistically different between treatments.

Kale and Tomato Yield

The summary of GLM for yield parameters including the number and weight of marketable and non-marketable leaves is provided in Table 1. The treatments resulted in significant differences in the yield parameters ($\chi^2 > 31.44$, $p < 0.001$). Here, we considered clean and undamaged leaves as marketable (suitable for human consumption). The number and weight of marketable leaves were consistently higher in push-pull plots compared to control plots during both long and short rain seasons (Fig. 7). In contrast, lower numbers and less weight of no-marketable leaves were observed in push-pull plots compared to control plots. Overall, 3.01 ± 0.17 and 1.54 ± 0.41 leaves/plant/week and 0.107 ± 0.011 and 0.013 ± 0.004 kg of leaves/plant/week were recorded in VIPP and control plots, respectively during short rain season. In the short rain season, 4.25 ± 0.51 and 2.92 ± 0.38 leaves/plant/week and 3.01 ± 0.17 and 1.54 ± 0.41 kg of

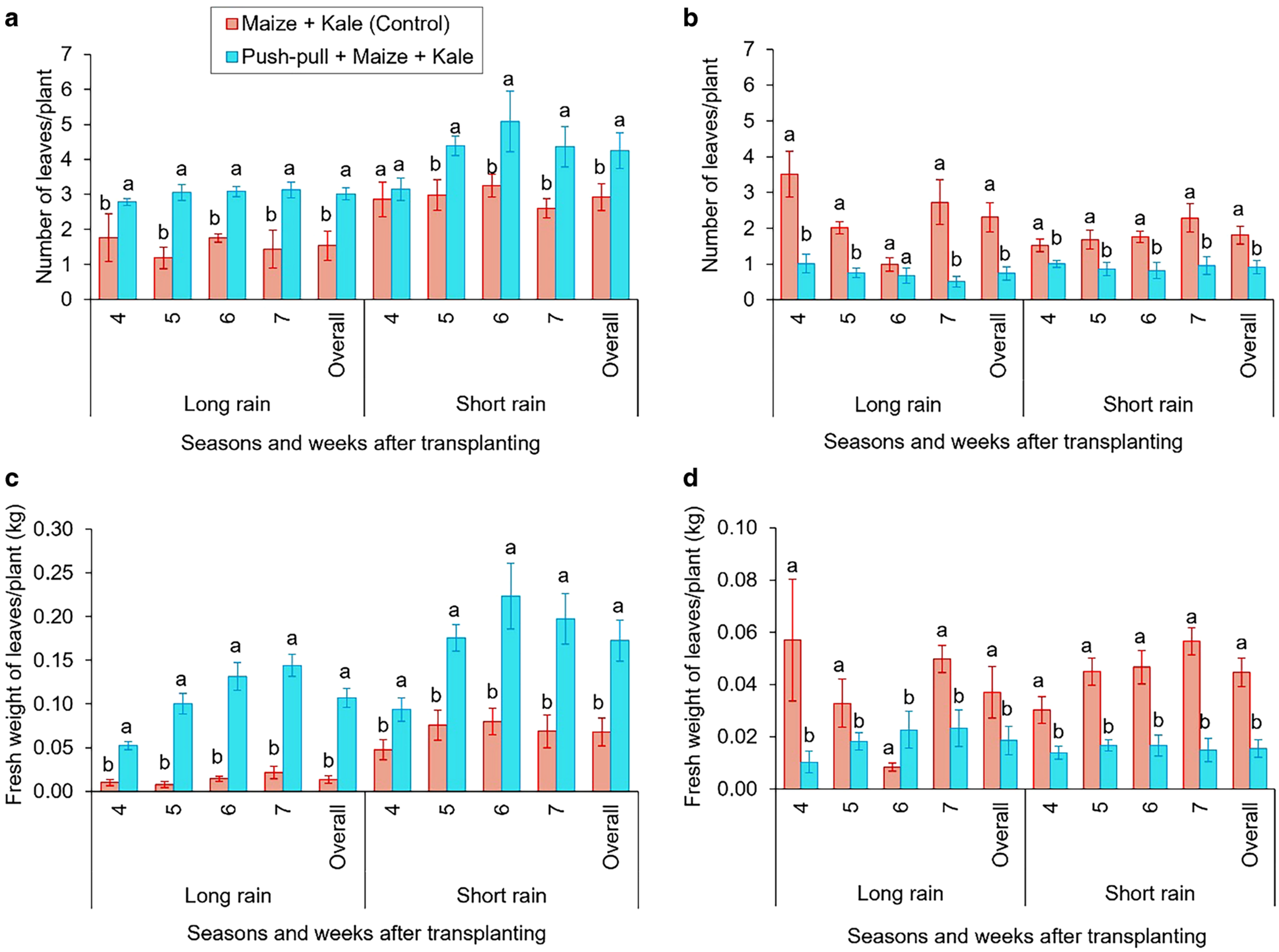

Fig. 8 Yield of kales (harvestable leaves) collected at different harvesting stages and seasons in push-pull (VIPP) and control plots as (**a**) number of marketable leaves, (**b**) number of non-marketable leaves, (**c**) weight of marketable leaves, (**d**) weight of non-marketable leaves. Different letters above the error bars denote significant differences between treatments

leaves/plant/week were recorded in push-pull and control plots, respectively (Fig. 8).

The summary of GLM for yield parameters including the number and weight of marketable and non-marketable tomato fruits is provided in Table 2. The treatments resulted in significant differences in the yield parameters ($\chi^2 >$ 39.75, $p < 0.001$). VIPP plots gave higher yield (number and weight of marketable fruits) and reduced yield loss in terms of the number and weight of non-marketable fruits of tomatoes than control plots during both long and short rain seasons (Fig. 9). Numerically, 5.44 ± 0.68 and 3.68 ± 0.06 fruits/plant/week and 0.49 ± 0.09 and 0.23 ± 0.04 kg of fruits/plant/week were recorded in push-pull and control plots, respectively during long rain season. While in short rain season, 6.32 ± 0.89 and 3.45 ± 0.60 fruits/plant/week and 0.33 ± 0.06 and 0.18 ± 0.03 kg of fruits/plant/week were recorded in push-pull and control plots, respectively.

Discussion

Pest Incidences and Damage Ratings On Kales

Our results show that a VIPP system differentially influences pest incidences and their damage in both kales and tomatoes. Aphids and DBM, the major pests in kale production, together with grasshoppers were consistently lower in the VIPP plots compared to the control underlying the importance of *in-situ* crop diversification in pest management. These findings corroborate several studies, which have associated habitat complexity in crop fields with reduced pest infestation. For example, companion cropping of cabbage with non-host vegetables resulted in reduced DBM infestations (Asare-Bediako et al. 2010). Similarly, such companion cropping has been widely associated with the suppression of aphids in various cropping systems (Lai et al. 2011; Ben-Issa et al. 2017a, b).

Table 2 Statistical summary of generalized linear models for yield parameters of tomato

Parameter	Independent variables	χ^2	Df	*p*-value
Number of marketable fruits	Season	0.286	1	0.59
	Treatment	39.75	1	**<0.001**
	Weeks after transplanting	10.79	3	**0.013**
	Season × Treatment	0.18	1	0.67
Number of non-marketable fruits	Season	0.01	1	0.92
	Treatment	38.60	1	**<0.001**
	Weeks after transplanting	17.60	3	**<0.001**
	Season × Treatment	4.34	1	**0.037**
Weight of marketable fruits	Season	22.52	1	**<0.001**
	Treatment	81.05	1	**<0.001**
	Weeks after transplanting	8.65	3	**0.034**
	Season × Treatment	5.69	1	**0.017**
Weight of non-marketable fruits	Season	2.99	1	0.084
	Treatment	57.74	1	**<0.001**
	Weeks after transplanting	15.62	3	**0.001**
	Season × Treatment	12.63	1	**<0.001**

The treatment consisted of vegetable integrated push-pull (VIPP) and control plots where experiments were conducted during long and short rain seasons

Yield data were assessed weekly at physiological maturity

The mechanisms for such pest suppression in companion cropping systems are broad. For example, non-host plants are known to disrupt the olfactory-guided location of hosts leading to lower infestations (Broad et al. 2008; Gurr et al. 2017). Alternatively, the complex habitats wrought by companion cropping can also lead to enhanced natural enemy diversity by either volatile mediated attraction (e.g. Khan et al. 1997; Mutua et al. 2024) or increased resources such as flowers and nectar availability (Sigsgaard et al. 2013; Straser et al. 2024) leading to increased pest parasitism. In our study system, the PPT has long been known to suppress pests by both volatile mediated insect behavioural manipulation where pests are repelled and lured away from the crop whilst parasitoids are recruited (Khan et al. 1997; Chidawanyika et al. 2014; Lang et al. 2022; Sobhy et al. 2022). Furthermore, the PPT has been linked with the conditioning of the soil where crop anti-herbivore secondary metabolites are activated to improve thereby reducing pest damage (Mutyambai et al. 2019, 2024; Bass et al. 2024; Lang et al. 2024). It is therefore plausible that vegetables introduced to form the VIPP benefit from a suite of these ecosystem services, in part or in full, leading to decreased pest activity.

Although the VIPP in our study showed efficacy against aphids, grasshoppers and DBM in kales, it did not influence the incidences of cabbage loopers suggesting that the impact of our model companion cropping system is not universally effective against all pests. Nevertheless, the occurrence of the loopers was relatively lower compared to the more devastating pests. In tomatoes, the VIPP did not influence incidences of thrips and bollworms underlying how the impact of such companion cropping may be species-specific. Taken together, our studies suggest the more generalist pests are less affected by the VIPP companion cropping. This is expected because, in nature, the behaviour of generalist insects tends to be modulated by a more complex integration of multiple cues (Bruce et al. 2010) to locate perfect hosts where feeding on alternatives due to chance encounters is often exploratory due to anti-herbivore feedback from plants including tactile and gustatory cues (Gols 2014; Ali and Agrawal 2012; Chakraborty et al. 2023). Such may have been the case in our study as the generalists tended to damage the crops relatively less compared to the specialist pests.

Insect population dynamics are known to be highly responsive to seasonality (Chidawanyika et al. 2020; Nyamukondiwa et al. 2022). In our study, there were differential effects of seasonality on pest incidences in both tomatoes and kales.

Disease Severity On Kale and Tomatoes

We observed early and late blight, black rot, leaf curl, leaf spot, mildew and anthracnose were common diseases observed on kales. In tomatoes, early and late blight, leaf curl and leaf spot were common diseases. The severity of black rot and leaf curl on kales and leaf spots on tomatoes were less in VIPP compared to control plots, implying *in situ* crop diversification can result in modification of host factors and reduce the susceptibility of crops to pests. Coupled with other practices such as crop rotation and removal of

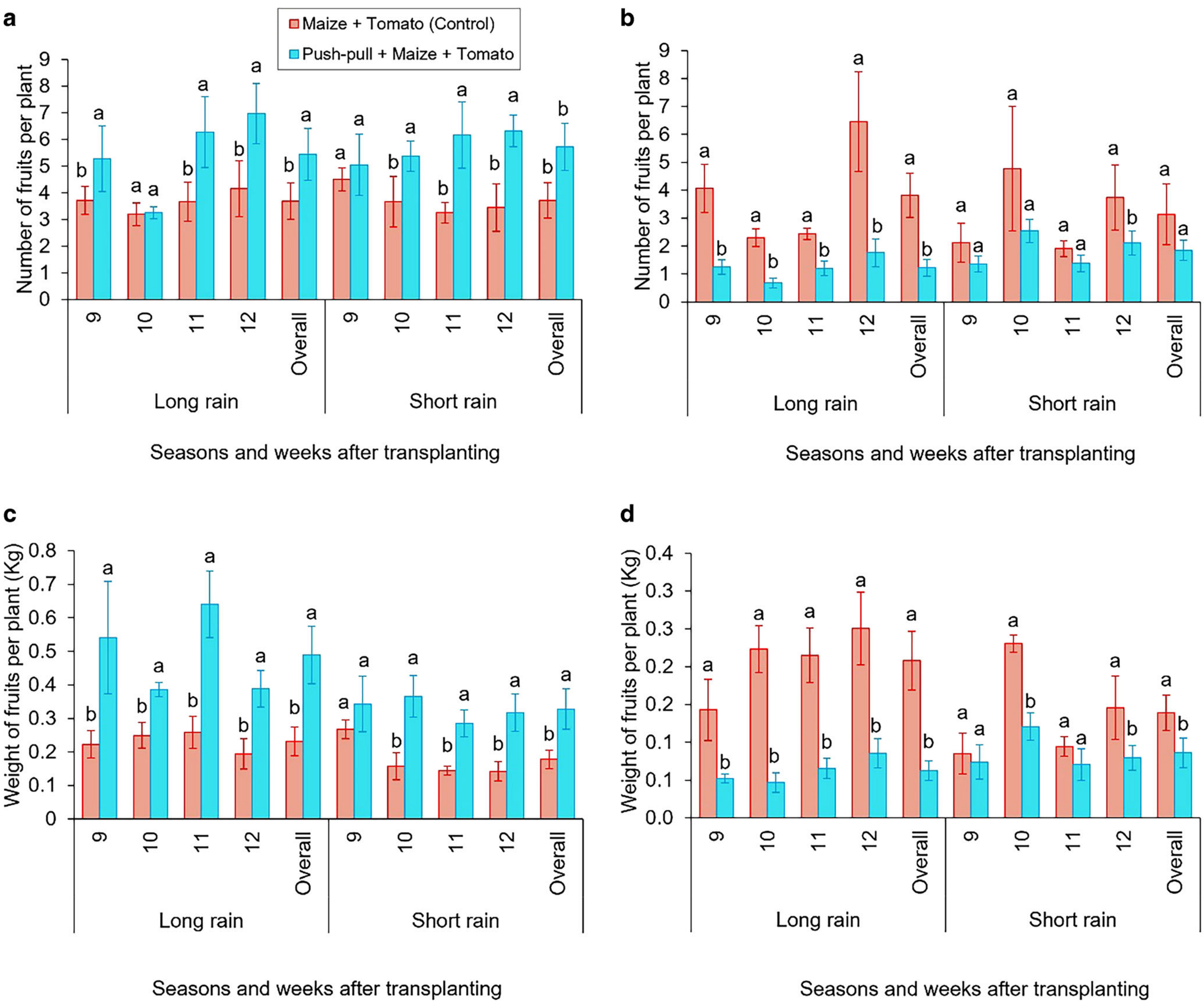

Fig. 9 Harvestable tomato fruits collected at different harvesting stages and seasons in push-pull (VIPP) and control plots as (**a**) number of marketable fruits, (**b**) number of non-marketable fruits, (**c**) weight of marketable fruits, (**d**) weight of non-marketable fruits. Different letters above the error bars denote significant differences between treatments

weeds, farmers can disrupt the disease cycles (Krupinsky et al. 2002).

Unlike other diseases, the severity of black rot and leaf curl on kales as well as blight and leaf spot on tomatoes was more pronounced during long rain than in short rain seasons. This demonstrates that long rain stimulates the severity of plant diseases. This corroborates findings by Khaliq et al. (2022) who reported a more apparent development of *Ascochyta* blight on cowpeas during prolonged rains. These further demonstrate the critical role of various components of the disease triangle including the host (crop types and cultivars), type of pathogens and environmental factors such as soil fertility, moisture, temperature and temperature on the development of diseases. Reportedly, cover crops can have twice as suppressive effects against pests and diseases when compared to intercropping or agroforestry (Beillouin et al. 2021). Interestingly, the other diseases were not different between vegetables planted in VIPP and control plots. This further demonstrates the disease management role of crop diversification may vary based on the number and types of crops as well as the type of plant pathogens. For instance, the practice of crop mixtures increases the disease host resistance index thereby improving disease reduction efficiency (Wang et al. 2021). Indeed, temporal and spatial crop diversification confers a lot of benefits including enhancing the regulation of pests, weeds and diseases and reducing pesticide use including herbicides, fungicides and insecticides (Struik and Kuyper 2017; Tooker and Frank 2012; Guinet et al. 2023).

Yield

In this study, we observed good quality and high yield of tomatoes and kales grown in VIPP plots compared to control plots. We attribute this gain in number and weight of marketable leaves of kale and tomato fruits to lower pest and disease pressure in VIPP plots compared to control plots. Furthermore, the high yield of vegetables in VIPP can be associated with the multifaceted benefits conferred by this technology including the presence of *Desmodium* which improves soil fertility through nitrogen fixation, live mulch to conserve soil moisture and ground cover to smother weeds. Indeed, PPT has been demonstrated to offer these benefits in addition to pest and striga weed management in cereal production (Khan et al. 2011).

Conclusions

Crop diversification such of the VIPP enhances crop protection, yield and quality of kales and tomatoes. Our results suggest that sustainable intensification practices such as the VIPP are viable alternatives for reducing the use of chemical pesticides whilst maintaining crop quality and yield. With further intensification options such as organic soil amendments such as manure, farmers may further enhance productivity whilst building a more bio-circular approach to their farming system. Whilst we demonstrate these crop protection benefits, there is need to investigate the mechanisms surrounding the trophic interactions including natural enemy responses and their efficacy in pest regulation. This will enable optimized and wider application of these intercropping approaches on the targeted pests.

Supplementary Information The online version of this article (https://doi.org/10.1007/s10343-024-01107-3) contains supplementary material, which is available to authorized users.

Funding The authors gratefully acknowledge the financial support for this research by the following organizations and agencies: Biovision Foundation through the project *Intensification of push-pull technology for improved food security, nutrition and incomes* (Grant number: BVDPP-001/2020-22); European Union through the *UPSCALE* project (Grant number: H2020-SFS-2019-2); The Ingvar Kamprad Elmtaryd Agunnaryd (IKEA) foundation through the "*Scaling regenerative black soldier fly farming along with vegetable push-pull cropping systems in rural Kenya, Rwanda and Uganda*" project (Grant number: 1175); the Swedish International Development Cooperation Agency (Sida); the Swiss Agency for Development and Cooperation (SDC); the Australian Centre for International Agricultural Research (ACIAR); the Norwegian Agency for Development Cooperation (Norad); the German Federal Ministry for Economic Cooperation and Development (BMZ); and the Government of the Republic of Kenya. The views expressed herein do not necessarily reflect the official opinion of the donors.

Funding Open access funding provided by University of the Free State.

Conflict of interest F. Chidawanyika, E.R. Omuse, L.O. Agutu, J.O. Pittchar, D. Nyagol and Z.R. Khan declare that they have no competing interests.

References

Adan IH, Asudi GO, Niassy S, Jalloh AA, Mutua JM, Chidawanyika F, Khamis F, Khan Z, Subramanian S, Dubois T, Mutyambai DM (2024) Comparative microbiome diversity in root-nodules of three Desmodium species used in push-pull cropping system. Front Microbiol 15:1395811

Ali JG, Agrawal AA (2012) Specialist versus generalist insect herbivores and plant defense. Trends Plant Sci 17(5):293–302

Asare-Bediako E, Addo-Quaye AA, Mohammed A (2010) Control of diamondback moth (Plutella xylostella) on cabbage (Brassica oleracea var capitata) using intercropping with non-host crops. Am J Food Technol 5(4):269–274

Bass E, Mutyambai DM, Midega CA, Khan ZR, Kessler A (2024) Associational effects of Desmodium intercropping on maize resistance and secondary metabolism. J Chem Ecol 50(5–6):299–318

Beillouin D, Ben-Ari T, Malézieux E, Seufert V, Makowski D (2021) Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob Change Biol 27:4697–4710

Ben-Issa R, Gautier H, Gomez L (2017a) Influence of neighbouring companion plants on the performance of aphid populations on sweet pepper plants under greenhouse conditions. Agr Forest Entomol 19(2):181–191

Ben-Issa R, Gomez L, Gautier H (2017b) Companion plants for aphid pest management. Insects 8(4):112

Brandmeier J, Reininghaus H, Pappagallo S, Karley AJ, Kiær LP, Scherber C (2021) Intercropping in high input agriculture supports arthropod diversity without risking significant yield losses. Basic Appl Ecol 53:26–38

Broad ST, Schellhorn NA, Lisson SN, Mendham NJ, Corkrey R (2008) Host location and parasitism of Brevicoryne brassicae in diversified broccoli cropping systems. Entomol Exp Appl 129(2):166–171

Bruce TJ, Midega CA, Birkett MA, Pickett JA, Khan ZR (2010) Is quality more important than quantity? Insect behavioural responses to changes in a volatile blend after stemborer oviposition on an African grass. Biol Lett 6(3):314–317

Chakraborty S, Gershenzon J, Schuster S (2023) Selection pressure by specialist and generalist insect herbivores leads to optimal constitutive plant defense. A mathematical model. Ecol Evol 13(12):e10763

Cheruiyot D, Chidawanyika F, Midega CA, Pittchar JO, Pickett JA, Khan ZR (2021) Field evaluation of a new third generation push-pull technology for control of striga weed, stemborers, and fall armyworm in western Kenya. Exp Agric 57(5–6):301–315

Cheruiyot D, Chidawanyika F, Midega CAO, Pittchar JO, Pickett JA, Khan ZR (2022) Field evaluation of a new third generation push-pull technology for control of striga weed, stemborers, and fall armyworm in western Kenya. Exp Agric 57:301–315

Chidawanyika F, Midega CA, Bruce TJ, Duncan F, Pickett JA, Khan ZR (2014) Oviposition acceptance and larval development of Chilo partellus stemborers in drought-stressed wild and cultivated grasses of East Africa. Entomologia Exp Applicata 151(3):209–217

Chidawanyika F, Mudavanhu P, Nyamukondiwa C (2019) Global climate change as a driver of bottom-up and top-down factors in agricultural landscapes and the fate of host-parasitoid interactions. Front Ecol Evol 7:80

Chidawanyika F, Chikowore G, Mutamiswa R (2020) Thermal tolerance of the biological control agent Neolema abbreviata and its potential geographic distribution together with its host Tradescantia fluminensis in South Africa. Biol Control 149:104315

Chidawanyika F, Muriithi B, Niassy S, Ouya FO, Pittchar JO, Kassie M, Khan ZR (2023) Sustainable intensification of vegetable production using the cereal 'push-pull technology': benefits and one health implications. Environ Sustain 6(1):25–34

de Graaff J, Kessler A, Nibbering JW (2011) Agriculture and food security in selected countries in Sub-Saharan Africa: diversity in trends and opportunities. Food Sec 3:195–213

Drinkwater LE, Midega CA, Awuor R, Nyagol D, Khan ZR (2021) Perennial legume intercrops provide multiple belowground ecosystem services in smallholder farming systems. Agric Ecosyst Environ 320:107566

Dvorak B, Yang S, Menotti T, Pace Z, Mehta S, Ali AK (2021) Native plant establishment on a custom modular living wall system in a humid subtropical climate. Urban For Urban Green 63:127234

Estrada-Carmona N, Sánchez AC, Remans R, Jones SK (2022) Complex agricultural landscapes host more biodiversity than simple ones: a global meta-analysis. Proc Natl Acad Sci USA 119:e2203385119

Gols R (2014) Direct and indirect chemical defences against insects in a multitrophic framework. Plant Cell Environ 37(8):1741–1752

Grez AA, Gonzalez RH (1995) Resource concentration hypothesis: effect of host plant patch size on density of herbivorous insects. Oecologia 103:471–474

Guinet M, Adeux G, Cordeau S, Courson E, Nandillon R, Zhang Y, Munier-Jolain N (2023) Fostering temporal crop diversification to reduce pesticide use. Nat Commun 14(1):7416

Gurr GM, Wratten SD, Landis DA, You M (2017) Habitat management to suppress pest populations: progress and prospects. Annu Rev Entomol 62(1):91–109

Hooper AM, Caulfield JC, Hao B, Pickett JA, Midega CAO, Khan ZR (2015) Isolation and identification of Desmodium root exudates from drought tolerant species used as intercrops against Striga hermonthica. Phytochemistry 117:380–387

Hu F, Feng F, Zhao C, Chai Q, Yu A, Yin W, Gan Y (2017) Integration of wheat-maize intercropping with conservation practices reduces CO_2 emissions and enhances water use in dry areas. Soil Tillage Res 169:44–53

Jalloh AA, Mutyambai DM, Yusuf AA, Subramanian S, Khamis F (2024) Maize edible-legumes intercropping systems for enhancing agrobiodiversity and belowground ecosystem services. Sci Rep 14(1):14355

Jeger MJ, Viljanen-Rollinson SLH (2001) The use of the area under the disease-progress curve (AUDPC) to assess quantitative disease resistance in crop cultivars. Theor Appl Genet 102:32–40

Khaliq I, Moore K, Sparks AH (2022) The relationship between natural rain intensity and Ascochyta blight in chickpea development. Eur J Plant Pathol 164(3):313–323

Khan Z, Midega C, Pittchar J, Pickett J, Bruce T (2011) Push–pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa: UK Government's foresight food and farming futures project. In: Sustainable intensification. Routledge, pp 162–170

Khan ZR, Ampong-Nyarko K, Chiliswa P, Hassanali A, Kimani S, Lwande W et al (1997) Intercropping increases parasitism of pests. Nature 388(6643):631–632

Krupinsky JM, Bailey KL, McMullen MP, Gossen BD, Turkington TK (2002) Managing plant disease risk in diversified cropping systems. Agron J 94(2):198–209

Lai R, You M, Lotz LAP, Vasseur L (2011) Response of green peach aphids and other arthropods to garlic intercropped with tobacco. Agron J 103(3):856–863

Lang J, Chidawanyika F, Khan ZR, Schuman MC (2022) Ecological chemistry of pest control in push-pull intercropping systems: What we know, and where to go? CHIMIA 76(11):906. https://doi.org/10.2533/chimia.2022.906

Lang J, Ramos SE, Reichert L, Amboka GM, Apel C, Chidawanyika F, Detebo A, Librán-Embid F, Meinhof D, Bigler L, Schuman MC (2024) Push–Pull intercropping increases the antiherbivore benzoxazinoid glycoside content in maize leaf tissue. ACS Agric Sci Technol 4(10):1074–1082

Liu R, Yang L, Zhang J, Zhou G, Chang D, Chai Q, Cao W (2024) Maize and legume intercropping enhanced crop growth and soil carbon and nutrient cycling through regulating soil enzyme activities. Eur J Agron 159:127237

Midega CA, Wasonga CJ, Hooper AM, Pickett JA, Khan ZR (2017) Drought-tolerant Desmodium species effectively suppress parasitic Striga weed and improve cereal grain yields in Western Kenya. Crop Prot 98:94–101

Midega CA, Pittchar JO, Pickett JA, Hailu GW, Khan ZR (2018) A climate-adapted push-pull system effectively controls fall armyworm, Spodoptera frugiperda (JE Smith), in maize in East Africa. Crop Prot 105:10–15

Mutua BK, Dubois T, Akutse KS, Muli B, Karanja EN, Mutyambai DM (2024) Electrophysiological and behavioral responses of cabbage aphid (Brevicoryne brassicae) to rosemary (Rosmarinus officinalis) volatiles, a potential push plant for vegetable push-pull cropping system. J Chem Ecol 50:778–789

Mutyambai DM, Bass E, Luttermoser T, Poveda K, Midega CA, Khan ZR, Kessler A (2019) More than "push" and "pull"? plant-soil feedbacks of maize companion cropping increase chemical plant defenses against herbivores. Front Ecol Evol 7:217

Mutyambai DM, Mutua JM, Kessler A, Jalloh AA, Njiru BN, Chidawanyika F, Dubois T, Khan Z, Mohamed S, Niassy S, Subramanian S (2024) Push-pull cropping system soil legacy alter maize metabolism and fall armyworm, Spodoptera frugiperda (Lepidoptera: Noctuidae) resistance through tritrophic interactions. Plant Soil 498(1):685–697

Noort MWJ, Renzetti S, Linderhof V, du Rand GE, Marx-Pienaar NJMM, de Kock HL, Magano N, Taylor JRN (2022) Towards sustainable shifts to healthy diets and food security in sub-Saharan Africa with climate-resilient crops in bread-type products: a food system analysis. Foods 11:135

Nyamukondiwa C, Machekano H, Chidawanyika F, Mutamiswa R, Ma G, Ma CS (2022) Geographic dispersion of invasive crop pests: the role of basal, plastic climate stress tolerance and other complementary traits in the tropics. Curr Opin Insect Sci 50:100878

Odermatt DM, Chidawanyika F, Mutyambai DM, Schmid B, Domeignoz-Horta LA, Tamiru A, Schuman MC (2024) Desmodium volatiles in "Push-Pull" agriculture and protection against the fall armyworm, Spodoptera frugiperda. Elife 13:RP100981

Ortega R, Miralles I, Domene MA, Meca D, Del Moral F (2024) Ecological practices increase soil fertility and microbial diversity under intensive farming. Sci Total Environ 954(327):176777

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot 114(8):1571–1596

R Core Team (2023) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna (https://www.R-project.org/)

Rakotomalala AA, Ficiciyan AM, Tscharntke T (2023) Intercropping enhances beneficial arthropods and controls pests: a systematic review and meta-analysis. Agric Ecosyst Environ 356:108617

Sigsgaard L, Betzer C, Naulin C, Eilenberg J, Enkegaard A, Kristensen K (2013) The effect of floral resources on parasitoid and host longevity: Prospects for conservation biological control in strawberries. J Insect Sci 13(1):104

Smith VH, McBride RC, Shurin JB, Bever JD, Crews TE, Tilman GD (2015) Crop diversification can contribute to disease risk control in sustainable biofuels production. Front Ecol Environ 13(10):561–567

Sobhy IS, Tamiru A, Chiriboga Morales X, Nyagol D, Cheruiyot D, Chidawanyika F, Subramanian S, Midega CA, Bruce TJ, Khan ZR (2022) Bioactive volatiles from push-pull companion crops repel fall armyworm and attract its parasitoids. Front Ecol Evol 10:883020

Stephens AE, Myers JH (2012) Resource concentration by insects and implications for plant populations. J Ecol 100(4):923–931

Straser RK, Daane KM, Stahl JM, Wilson H (2024) Floral resources enhance fitness of the parasitoid Hadronotus pennsylvanicus (Hymenoptera: Scelionidae) but not biological control of its host Leptoglossus zonatus (Heteroptera: Coreidae). Environ Entomol 53(2):213–222

Struik PC, Kuyper TW (2017) Sustainable intensification in agriculture: the richer shade of green. A review. Agron Sustain Dev 37:1–15

Sun Y, Chen L, Zhang S, Miao Y, Zhang Y, Li Z, Zhao J, Yu L, Zhang J, Qin X, Yao Y (2022) Plant interaction patterns shape the soil microbial community and nutrient cycling in different intercropping scenarios of aromatic plant species. Front Microbiol 13:888789

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci USA 108(50):20260–20264

Tobisch C, Rojas-Botero S, Uhler J, Kollmann J, Müller J, Moning C, Redlich S, Steffan-Dewenter I, Benjamin C, Englmeier J, Fricke U (2023) Conservation-relevant plant species indicate arthropod richness across trophic levels: Habitat quality is more important than habitat amount. Ecol Indic 148:110039

Tooker JF, Frank SD (2012) Genotypically diverse cultivar mixtures for insect pest management and increased crop yields. J Appl Ecology 49(5):974–985

Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A (2012) Global food security, biodiversity conservation and the future of agricultural intensification. Biol Conserv 151(1):53–59

Wang YP, Pan ZC, Yang LN, Burdon JJ, Friberg H, Sui QJ, Zhan J (2021) Optimizing plant disease management in agricultural ecosystems through rational in-crop diversification. Front Plant Sci 12:767209

Weltin M, Hüttel S (2023) Sustainable intensification farming as an enabler for farm eco-efficiency? Environ Resour Econ 84(1):315–342