

Article

Field Margin Plants Support Natural Enemies in Sub-Saharan Africa Smallholder Common Bean Farming Systems

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Abstract: Flower-rich field margins provide habitat and food resources for natural enemies of pests (NEs), but their potential, particularly in the tropics and on smallholder farms, is poorly understood. We surveyed field margins for plant-NE interactions in bean fields. NEs most often interacted with *Bidens pilosa* (15.4% of all interactions) and *Euphorbia heterophylla* (11.3% of all interactions). In cage trials with an aphid-infested bean plant and a single flowering margin plant, survival of *Aphidius colemani*, the most abundant parasitoid NE in bean fields, was greater in the presence of *Euphorbia heterophylla* than *Bidens pilosa*, *Tagetes minuta*, and *Hyptis suaveolens*. UV-fluorescent dye was applied to flowers of specific field margin plant species and NEs sampled from within the bean crop and field margins using sweep-netting and pan-traps respectively. Captured insects were examined for the presence of the dye, indicative of a prior visit to the margin. Lady beetles and assassin bugs were most abundant in plots with *B. pilosa* margins; hoverflies with *T. minuta* and *Parthenium hysterophorus* margins; lacewings with *T. minuta* and *B. pilosa* margins. Overall, NEs benefitted from field margin plants and those possessing extra floral nectaries had an added advantage. Field margin plants need careful selection to ensure benefits to different NE groups.

Keywords: aphid; conservation biocontrol; parasitoid; *Aphidius colemani*; floral resource plant; field margin

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1. Introduction

Common bean (*Phaseolus vulgaris*) is important for food security for millions of people in sub-Saharan Africa (SSA). It is a major source of dietary protein, carbohydrates, and minerals [1] and contributes to soil fertility by fixing nitrogen with yield benefits for subsequent crops [2–5]. However, common bean production is constrained by several factors including insect pests [6–9]. Synthetic pesticides are the primary technology used to manage bean pests but this has adverse effects on human health, contributes to biodiversity loss and leads to the resurgence of secondary pests [8,10]. More natural pest regulating approaches are required such as conservation biological control but this has not been adequately addressed in sub-Saharan Africa [11,12].

For example, natural enemies (NEs) that predate or parasitize insect pests can be a key component of sustainable pest management [13–15]. NEs benefit from non-crop plants in agricultural systems through the provision of shelter, nectar, and pollen for effective biological control [11,16,17]. It is possible to optimize the pest management contribution of NEs by managing field margin plants. However, to maximize the benefit of field

margin plants, it is necessary to understand the specific advantages of each flowering plant to NEs to improve natural pest regulation (NPR) and increase crop productivity. For instance, some flowers are tubular and lack nectaries and these are not suitable for NEs [18–22].

Most studies focus on NEs and the floral resource requirements in a specific context; either the benefit of the plants on NE in a controlled environment (e.g., cage) or whether the NEs interact in the field with the margin plants and enhance NPR [11,12,16,17]. However, combining this information could help better understand which plants will be most valuable in specific supporting conservation biological control approaches.

Field margin plants differ in their attractiveness to natural enemies [23] and few studies have been conducted on the contribution of these plants to supporting NEs of bean pests. Thus, we intended to test the following hypotheses. 1) Field margin plants influence assemblage natural enemies on beans; 2) Specific field margin plants influence differently the fecundity and survival of NEs on beans 3) NEs of bean pests use specific margin plants before migrating into the crop to provide NPR services.

2. Results

2.1. Interactions between Natural Enemies and Field Margin Plants

This field trial surveyed the interactions of the field margin plant species with NEs in bean fields. When observing NE-plant interactions on transect walks on bean fields, most insect groups investigated had interactions with most species of plant investigated. Overall, 5597 NE-plant interactions were observed, and the greatest number of interactions were recorded with the margin plant *B. pilosa* (861 interactions) followed by *E. heterophylla* (631). Parasitoid wasps were the NE group with the greatest number of observed interactions with field margin plants (724 interactions) (Figure 1).

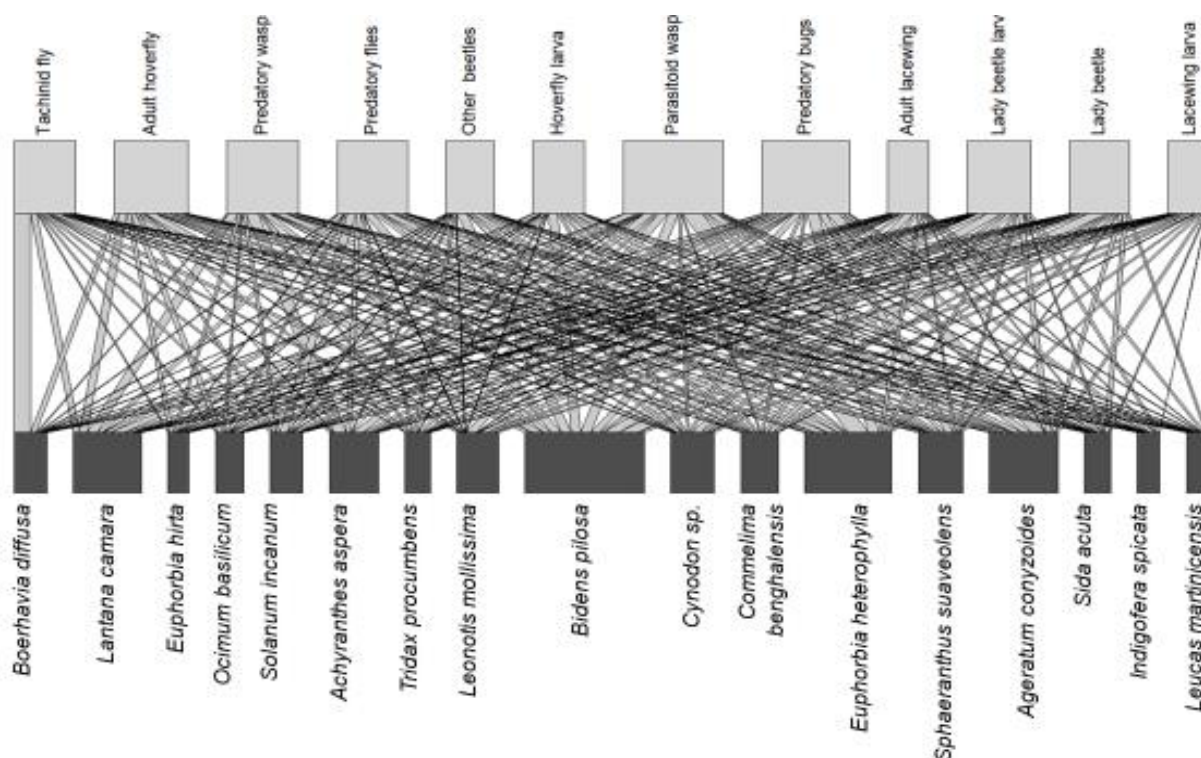


Figure 1. Interactions of natural enemies with field margin plants observed during transect walks in margins of bean fields over 12 months through visual observation with *Bidens pilosa* having a high number of interactions with natural enemies compared to other field margin plants. The lower row shows plant species present and the upper row shows the natural enemy guilds; the width of the linking bars indicates the frequency of the interactions observed.

2.2. Effects of Flowering Plant Resources on Parasitism and Survival of *A. colemani*

In the controlled environment (cages) we investigated the potential of the key field margin plants to support their survival of the *Aphis fabae* parasitoid *A. colemani* and optimize parasitism. When aphid-infested bean plants were caged with *A. colemani* parasitoids and a flowering margin companion plant, survival of *A. colemani* was enhanced on all plant species compared to the negative control demonstrating that nectar from all species tested supported NE survival. However, the effect differed significantly among the different flower treatments ($p < 0.001$; Figure 2). The plant that supported significantly improved survival of *A. colemani* compared to other plants and the positive control was *E. heterophylla*. There was no significant difference ($F_{4,16} = 1.126$, $p = 0.381$) between the number of mummies produced by *A. colemani* given access to any floral resource plants or the positive control (Figure 3).

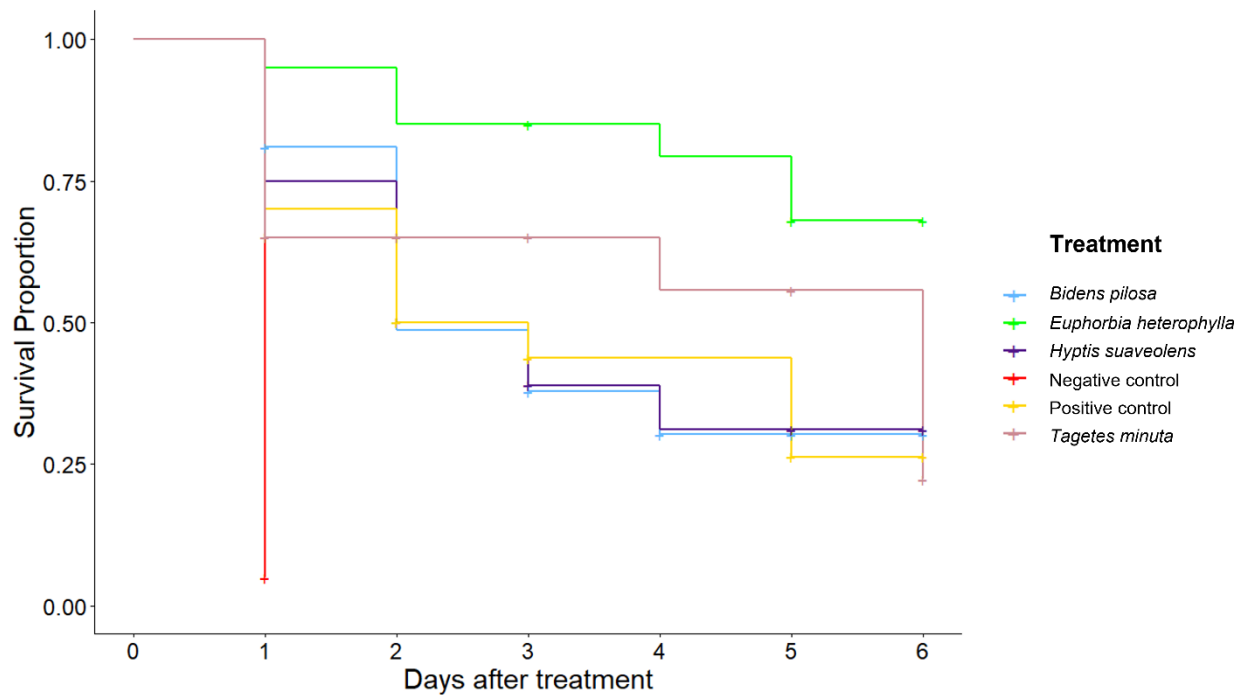


Figure 2. Survival of *A. colemani* when provided different field margin plant species, sugar water (positive control), or only water (negative control). A '+' represents a censored individual.

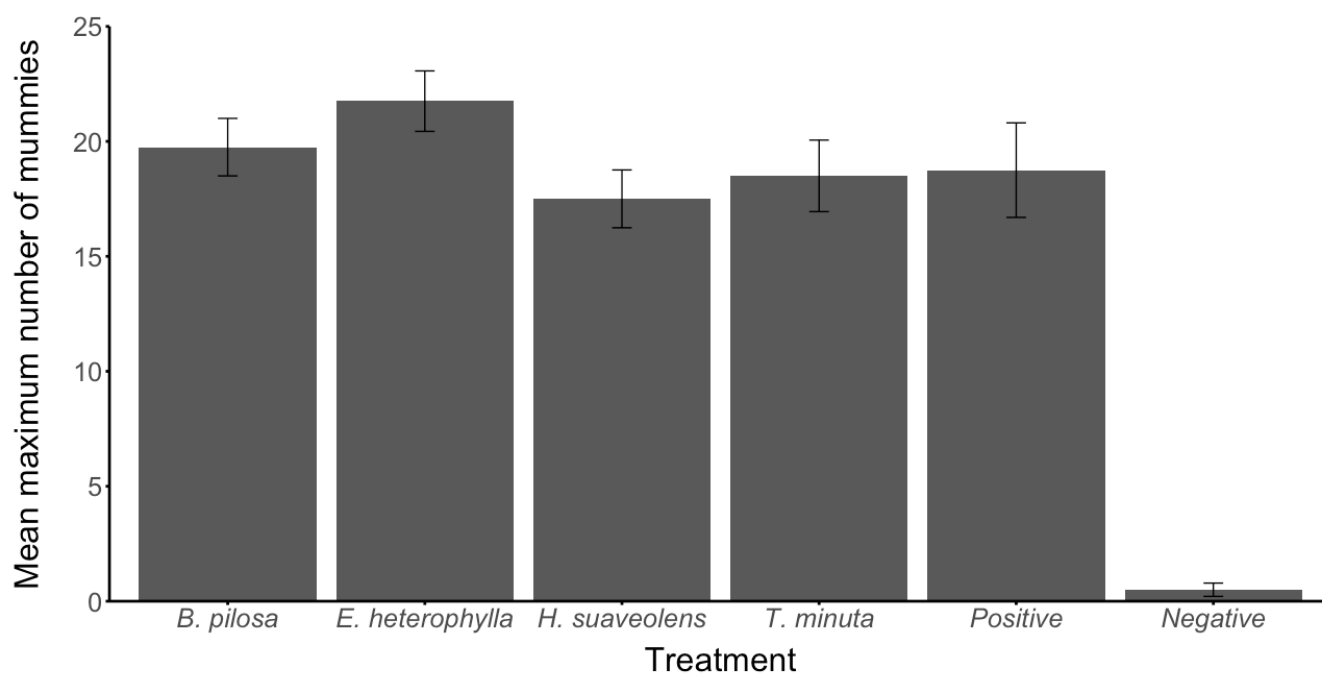


Figure 3. The mean number of *A. fabae* mummies produced per cage containing four females and two males of *A. colemani*. Treatments: *B. pilosa*-*Bidens pilosa*; *E. heterophylla*-*Euphorbia heterophylla*; *H. suaveolens*-*Hyptis suaveolens*; *T. minuta*-*Tagetes minuta*; Positive-Positive control; Negative-Negative control

2.3. Effect of Different Field Margin Plants in Supporting Natural Enemies in Bean Fields Fluorescent Dye

On a station trial, we cultivated bean plots surrounded by one of three field margin plant species and treated the flowers with a fluorescent dye. We then captured insects in the crop (via sweep netting) and examined them for the presence of the dye, which identified the insects that had interacted with the field margin before moving into the crop, as well as pan-trapping within the margins. Lady beetles, hoverflies, assassin bugs, and lacewings differed in the number of fluorescent-labelled individuals captured the crop, according to the surrounding plant species (Table 1). Lady beetles, lacewings and assassin bugs with fluorescent dye were particularly numerous in the *B. pilosa*-edged plots (and for lacewings, *T. minuta*), indicating these species regularly used *B. pilosa* before moving into the crop. Conversely, hoverflies were more numerous in plots surrounded by dye-marked *P. hysterophorus* and *T. minuta*. Plots with *P. hysterophorus* margins were much less frequently used by lady beetles, lacewings and assassin bugs (Table 1).

The number of natural enemies caught in pan traps in field margins also varied significantly depending on which field margin plant was present (Table 2), following similar patterns to the crop. Again, *B. pilosa* plots favoured lady beetles, assassin bugs and lacewings and parasitoid wasps within the margins, while *T. minuta* and *P. hysterophorus* favoured hoverflies in the margins (Table 2).

Table 1. Mean \pm (SEM) numbers of natural enemies labelled with UV fluorescent powder within bean crops surrounded by different field margin plants. Different letters indicate significant differences between treatments within natural enemy groups. Significant differences were calculated using a GLM with Poisson distribution followed by pairwise comparisons and Holm multiple comparisons test.

| Treatment | Mean Number of Natural Enemies (\pm SEM) | | | | | |
|---------------------------------|---|--------------------|-------------------|-------------------|-------------------|-------------------|
| | Lady Beetle | Hoverfly | Assassin Bug | Lacewing | Parasitoid Wasp | Long-legged Fly |
| <i>Biden pilosa</i> | 9.50 \pm 2.02 a | 2.50 \pm 0.65 b | 5.25 \pm 0.95 a | 6.50 \pm 1.04 a | 2.00 \pm 0.82 a | 1.50 \pm 0.87 a |
| Control (no plant) | 2.50 \pm 1.04 b | 5.50 \pm 2.26 ab | 0.75 \pm 0.48 b | 2.00 \pm 0.41 b | 1.75 \pm 0.63 a | 1.75 \pm 0.48 a |
| <i>Parthenium hysterophorus</i> | 4.25 \pm 0.85 b | 7.25 \pm 0.48 a | 2.25 \pm 0.48 b | 2.00 \pm 0.82 b | 2.25 \pm 0.75 a | 1.75 \pm 0.48 a |
| <i>Tagetes minuta</i> | 6.25 \pm 1.03 ab | 8.25 \pm 0.85 a | 0.75 \pm 0.48 b | 7.00 \pm 1.47 a | 3.25 \pm 1.32 a | 2.75 \pm 0.48 a |

Values followed by the same letters (a and b) within the column are not significantly different ($p < 0.05$).

Table 2. The mean \pm (SEM) number of natural enemies caught in pan traps in field plots with different field margin plants. Different letters indicate significant differences between treatments within natural enemy groups. Significant differences were calculated using a GLM with Poisson distribution followed by pairwise comparisons and Holm multiple comparisons test.

| Treatment | Mean Number of Natural Enemies (\pm SEM) | | | | | |
|---------------------------------|---|-----------------------|-----------------------|-----------------------|----------------------|----------------------|
| | Lady Beetle | Hoverfly | Assassin Bug | Lacewing | Parasitoid Wasp | Long-legged Fly |
| Control (no plant) | 1.83 (\pm 0.63) a | 1.92 (\pm 0.54) a | 1.25 (\pm 0.70) a | 1.50 (\pm 0.86) a | 1.75 (\pm 0.49) a | 1.75 (\pm 0.63) a |
| <i>Bidens pilosa</i> | 5.92 (\pm 1.05) b | 2.67 (\pm 0.77) ab | 3.75 (\pm 0.35) b | 3.50 (\pm 0.42) b | 5.31 (\pm 1.53) b | 1.67 (\pm 0.45) a |
| <i>Parthenium hysterophorus</i> | 2.17 (\pm 1.95) a | 4.50 (\pm 0.82) b | 2.42 (\pm 0.78) ab | 2.42 (\pm 0.86) ab | 3.23 (\pm 0.93) b | 1.08 (\pm 0.34) a |
| <i>Tagetes minuta</i> | 3.33 (\pm 0.88) a | 4.58 (\pm 0.83) b | 3.42 (\pm 1.23) b | 3.58 (\pm 0.93) b | 4.58 (\pm 1.32) b | 0.75 (\pm 0.22) a |

Values followed by the same letters (a and b) within the column are not significantly different ($p < 0.05$).

3. Discussion

The composition of plants for a field margin that effectively supports natural enemies (NEs) may require different plant communities than for pollinators, though some plants may be providing nectar and pollen to both natural enemies and pollinators [24]. The species that support NEs most effectively in East Africa are still poorly understood. Some common field margin species such as *E. heterophylla* (Euphorbiaceae), *P. hysterophorus*, *B. pilosa*, *T. minuta* (Asteraceae) and *H. suaveolens* (Lamiaceae) are invasive to SSA. However, their potential has been explored for pest control, pollination and medicinal activities [11,16,25–27]. Our study aimed to determine which field margin plant species in SSA were beneficial to NEs in smallholder bean farms. The transect walk showed that NEs interact with multiple field margin plant species, although certain species had a higher number of interactions (*B. pilosa* and *E. heterophylla*). NEs depend on pollen and nectar from the plants and plants provide alternative hosts in the absence of crops [28–35]. Similar results were found in a recent study by Arnold et al. [16] that showed that *B. pilosa* and *Euphorbia* sp. were preferred by natural enemies and pollinators in SSA. The use of *B. pilosa* and *E. heterophylla* by NEs could indicate that they provide valuable food or habitat resources. The observed interactions of NEs with *E. heterophylla* concur with the study by Patt [36] showing that this species provided nectar for lady beetles (*Coelophora inequalis*, *Cryptolaemus montrouzieri*, and *Harmonia axyridis*). Similarly, *B. pilosa* is effective in attracting populations of the lady beetles (*Cycloneda sanguinea*) and hoverflies (*Pseudodoros* sp.) [37,38]. In addition, chemical cues from the *B. pilosa* play a role in attracting natural enemies [39].

In station trials, we found that plots surrounded by *B. pilosa* margins were used frequently by lady beetles, parasitoids, and assassin bugs; *T. minuta* field margins were associated with catches of hoverflies, assassin bugs, lacewings, and parasitoids and *P. hysterophorus* only with higher numbers of hoverflies and parasitoids. Furthermore, NEs caught inside the field crops with fluorescent dye indicate the insects visit the flowers (possibly consuming nectar and/or pollen) before moving into the crop where they can

provide pest control benefits. Relatively few long-legged flies and parasitoids were captured with the fluorescent dye, but this could be due to their small size rather than lack of interaction with field margin species. Previous studies have shown the importance of *B. pilosa*, *T. minuta*, and *P. hysterothorus* in supporting NEs [27,37–40]. Floral resources from non-crop habitats are expected to support NPR by NEs [40–46]. Thus, selecting suitable plants for NEs is an important component of agricultural landscaping as some plants will be better at supporting NEs. For instance, providing adult hoverflies with floral resources can enhance biological control by their larvae [47,48]. Also, pollen from some plants is superior to others in enhancing the performance of NEs [49] and this might explain why in our data one plant species *E. heterophylla* supported *A. colemani* better than the positive control.

Significantly more parasitoids were recorded in plots with field margin plants compared to the control (without field margin plants). In the transect walks parasitoids were also the NE group with the most plant interactions. This could suggest that parasitoids are a NE group for which field margin plants are particularly important; providing of carbohydrates, amino acids, and vitamins in nectar that enhance their pest controlling activities and optimize their metabolism [29,30,35]. This was demonstrated using a cage trial experiment, which showed that all plants i.e., *B. pilosa*, *H. suaveolens*, *T. minuta* and *E. heterophylla* resulted in improved *A. colemani* survival and similar to the positive control which provided an in-cage carbohydrate food supply. Survival of parasitoids on *E. heterophylla* was greater even than the positive control and all other plants suggesting that this species provided a greater nutritional benefit to *A. colemani*. Our results concur with similar studies, showing that access to flowers of several plant species prolongs the lifespan and increases parasitism by *A. colemani*. For instance, studies on *A. colemani* and *Diadegma insulare* have shown improved performance compared with controls both in the field and when caged with flowering plant species such as *Fagopyrum esculentum*, *Conium maculatum*, *Photinia × fraseri*, *Brassica kaber*, *Barbarea vulgaris*, *Salvia apiana*, *Ligustrum japonicum*, *Lantana camara*, *Eriogonum fasciculatum*, *Daucus carota* and *Thlaspi arvense* [50–53].

One of the reasons that *B. pilosa*, *H. suaveolens* and *E. heterophylla* supported *A. colemani* survival during the cage trial and that *B. pilosa* and *E. heterophylla* had high numbers of interactions with NEs in field trials could be the presence of extrafloral nectaries on these species [36,54–56]. Extrafloral nectaries are easily accessible, and the nectar composition differs from floral nectar and may be secreted differently [57]. Extrafloral nectar sugars are typically more concentrated than floral nectar, and normally it is present in larger volumes and secreted for a longer period [49,57]. Plants with extrafloral nectaries can be particularly important for NEs, and attractive to parasitoids [58] because these insects have mouthparts that are not suited to feeding on floral corollas; hence, they depend on plants with extrafloral or otherwise exposed flower nectaries [19,59,60]. Indeed, *E. heterophylla* produces extrafloral nectar right up to fruit maturation, possibly to provide food resources to attract natural enemies of seed and fruit pests [36].

Although *T. minuta* does not have extrafloral nectaries, it supported *A. colemani* survival in cage trials and plots while *T. minuta* field margins had greater numbers of hoverflies, assassin bugs, lacewings, and parasitoids compared to control plots. This concurs with previous reports that *T. minuta* supports NEs. *T. minuta* increased the longevity of the egg parasitoid *Trichogramma minutum*, which enhanced the parasitism of the *Grapholita molesta* eggs [40]. Other species of *Tagetes*, including *T. erecta*, increased the longevity of *Cyrtorhinus lividipennis*, a NE of rice brown planthopper (*Nilaparvata lugens*) [61]. The extrafloral resources from the field margin plants could have additional benefits to natural enemies and support biological control. Incorporating those field margins with extrafloral resources could bring positive effects for pest control in bean fields.

4. Materials and Methods

4.1. Interactions between Natural Enemies and Field Margin Plants

This field trial was carried out at Kwa Sadala Village in Hai District, Kilimanjaro region (3° 10' 0" S, 37° 10' 0" E). Eight sites with a high diversity margin and eight sites with a poor margin were visited. The high and poor diversity fields were determined by measuring the plant diversity in each farm before the selection of the sites. A transect walk along one margin, for the length of the field, was done and the visual observation of the NEs visits to the specific plant flowers was recorded. The sampling was conducted monthly during a year and this coincided with specific bean crop development stages (1,5,9,14 etc weeks after bean emergence).

4.2. Effect of Flowering Plant Resources on Parasitism and Survival of *A. colemani*

Aphidius colemani adults were obtained from *A. fabae* mummies collected from bean fields at Kwa Sadala in Hai District, Kilimanjaro region. *A. colemani* was selected for the cage trial because it has been reported as a primary parasitoid of *A. fabae* in SSA [12]. Also, this species is commercially produced for the biological control of many aphid species [62,63].

They were reared on potted bean plants infested with *A. fabae* in a wooden netted cage 30×30×60 cm. The plants were watered every three days. The *A. fabae* colonies were established from insects collected from farmers' fields at Kwa Sadala village, the location of the field trials.

Bean seeds were grown in pots, then after five weeks, they were infested with 60 *A. fabae* (nymphs and apterous adults) [64]. The seeds from four field margin weeds (*T. minuta*, *H. suaveolens*, *E. heterophylla*, *B. pilosa*) were germinated in pots before planting out in fields. The experiment consisted of six treatments (*T. minuta*, *H. suaveolens*, *E. heterophylla*, *B. pilosa*, positive control, negative control), and each treatment was replicated four times. Each cage contained one of these treatments with a potted bean plant infested with *A. fabae*. The positive control contained 10% sugar solution (glucose) as often as it was needed [65] and a potted bean plant infested with *A. fabae*, while the negative control had only a potted bean plant infested with *A. fabae*. Plants were watered every three days.

After leaving the aphids in the cage for 24 h to acclimatize, four female parasitoids and two male parasitoids were introduced to each cage. For the first seven days, the number of live parasitoids and mummies was counted daily to determine the survival of the first generation. Following this, the counting was done three times a week. The number of parasitoids that emerged from mummies was recorded. The experiment was carried out for one entire lifecycle of parasitoids (approximately one month). The parasitoids and aphids were maintained under controlled conditions with an average temperature of 25–27 °C, 66–68% R.H., and under natural lighting.

4.3. Effect of Different Field Margin Plants in Supporting Natural Enemies in Bean Fields

A field experiment was carried out at Kwa Sadala Village in Hai District, Kilimanjaro region to monitor NE movement between field margins and crops. Three plant species introduced above, *T. minuta*, *B. pilosa*, and *P. hysterophorus* were cultivated as the field margin. We initially selected *B. pilosa* and *E. heterophylla* due to the high number of interactions in the transect walk experiment. However, *E. heterophylla* failed to develop in the field, and thus other plants (*T. minuta*, *B. pilosa* and *P. hysterophorus*) were selected for subsequently field studies as they occur frequently in SSA, have previously shown associations with beneficial insects [11,16,25,27] and are therefore straightforward for smallholders to acquire [26,66].

The experimental layout was composed of four treatment plots containing common bean (*P. vulgaris*) with four replications, 0.5 m field margin plants surrounded by three plots in each replication, each plot with the specific field margin plant, and the remaining plot was the control without a field margin. The plots measured 15×15 m, and the distance

between plots was 15 m (Figure 4). During the flowering period of beans in the fifth week, powdered UV fluorescent dye (Baker Ross Ltd., Halow, UK) was applied in the field margin plant flowers using a soft paintbrush. After 24 h, natural enemies were collected inside the field using sweep nets, then examined using a UV torch (365 nm; UVGear, Surrey, UK) to detect any fluorescent dye. This allowed the identification of insects that had visited the different field margin plants before being caught in the crop fields as an indication of the potential value of different species to different NEs. Pan traps were also used to collect NEs in the field margins [11], two pan traps were placed in the field margin of each plot and natural enemies were sampled for three months (April, May, and June) coinciding with bean development stages. The collections were preserved in 70% ethanol for further identification.

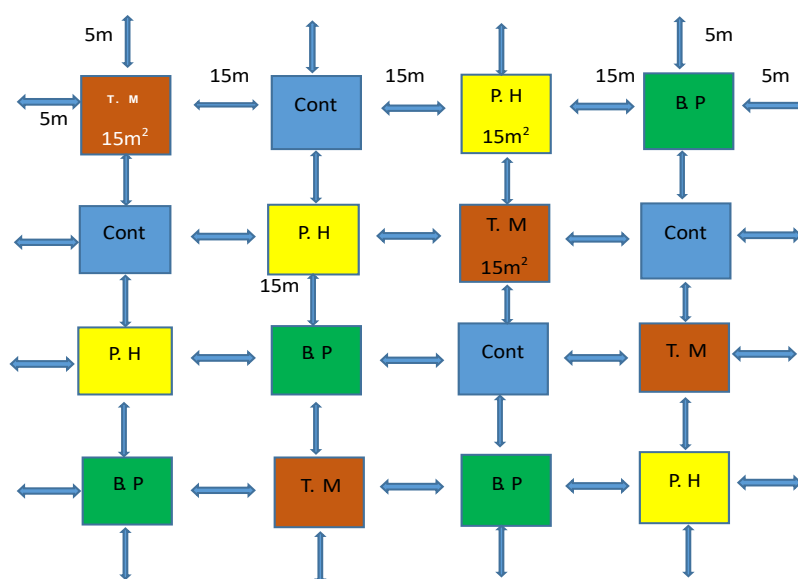


Figure 4. Field margin plants surrounding bean experimental plots for the fluorescent dye trial: T.M-*Tagetes minuta*; Cont-Control; P.H-*Parthenium hysterophorus*; B.P-*Biden pilosa*.

4.4. Statistical Analysis

The interactions between NEs and different field margin plants were plotted using the ‘bipartite’ package [67] in R (RStudio Version 1.2.1335). Insects caught in field margins using pan traps were grouped into functional categories of NEs; catch distributions were checked for normality using Shapiro-Wilk. To assess the effect of field margin plants on the number of natural enemies caught, a histogram was plotted to assess the distribution of the data. Following this, GLM with Poisson distribution (RStudio Version 1.2.1335) was selected as the data were not normally distributed. The fit of models was assessed with Chi-squared goodness of fit test and all were found to follow this distribution. The month of sampling and field margin plant species were included in the GLM as covariates without interactions. Following this, pairwise comparisons were done with the Holm multiple comparisons test in the ‘emmeans’ package [68].

The number of *A. colemani* surviving in cage trials was analyzed over 6 days using the Kaplan-Meier estimator of survival in R (RStudio Version 1.2.1335; [69]). For this analysis surviving individuals were censored at the end of the experiment and individuals were censored if it was not possible to monitor their survival for the duration of the experiment (e.g., for escaped individuals). Pairwise comparisons between treatments were then performed using a log-rank test with Benjamini-Hochberg correction. To assess the parasitism of *A. colemani*, the number of mummies in each cage was analyzed using an ANOVA. Prior to the analysis, the negative control was removed due to lack of variance and the normality of the remaining data was assessed using the Shapiro-Wilk test [50].

To analyse the number of insects labelled with the fluorescent dye and those captured in the field margin, GLM assuming Poisson distribution with a log link was used followed by pairwise comparisons and Holm multiple comparisons test. The normality was assessed using the Shapiro-Wilk test.

5. Conclusions

Flowering plants provide food and shelter for NEs and can promote NPR in crops. Our study highlights the potential of the field margin plants in supporting populations of NEs in smallholder farms and shows that conservation biological control could be used to promote NEs in these agro-ecosystems. Certain plant species appear to be preferred by different NE groups and provide different benefits. In transect walks the highest number of NEs were observed interacting with *B. pilosa* and *E. heterophylla*. In addition, *B. pilosa*, *T. minuta*, and *P. hysterophorus* supported different groups of natural enemies when planted as a field margin. NE groups were shown to interact with flowers of these field margin plants, suggesting that they are supported by the provision of nectar and pollen. This is corroborated by cage trials where *B. pilosa*, *E. heterophylla*, *H. suaveolens*, and *T. minuta* enhanced the survival of *A. colemani*, most likely through the provision of nectar [27,37,39,40,70]. However, it is important to consider the wider implications of using these plants in conservation biological control, for example, *P. hysterophorus* is toxic [71,72] and other plants may be invasive to the area and present a challenge as weeds. Some field margin plant species might also provide food and shelter for specific pests, and therefore it is crucial to study the biology of the host plants and how they interact with pests.

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Data Availability Statement: Data is contained in supplementary material

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Conflicts of Interest: The authors declare that they have no conflict of interest

References

1. Temba, M. C., Njobeh, P. B., Adebo, O. A., Olugbile, A. O., & Kayitesi, E. The role of compositing cereals with legumes to alleviate protein-energy malnutrition in Africa. *Int. J. Food Sci.* **2016**, *51*, 543–554. <https://doi.org/10.1111/IJFS.13035>
2. Franke, A. C., Laberge, G., Oyewole, B. D., & Schulz, S. A comparison between legume technologies and fallow, and their effects on maize and soil traits, in two distinct environments of the West African savannah. *Nutr. Cycl. Agroecosystems.* **2008**, *82*, 117–135. <https://doi.org/10.1007/s10705-008-9174-2>
3. Franke, A. C., Van den Brand, G. J., Vanlauwe, B., & Giller, K. E. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agric. Ecosyst. Environ.* **2018**, *261*, 172–185. <https://doi.org/10.1016/j.agee.2017.09.029>
4. Kamanga, B. C. G., Waddington, S. R., Robertson, M. J., & Giller, K. E. Risk analysis of maize-legume crop combinations with smallholder farmers varying in resource endowment in central Malawi. *Exp. Agr.* **2010**, *46*, 1. <https://doi.org/10.1017/S0014479709990469>

5. Ojiem, J. O., Franke, A. C., Vanlauwe, B., De Ridder, N., & Giller, K. E. Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *Field Crops Res.* **2014**, *168*, 75–85. <https://doi.org/10.1016/J.FCR.2014.08.004>
6. Abate, T., van Huis, A., & Ampofo, J. K. O. Pest management strategies in traditional agriculture: an African perspective. *Annu. Rev. Entomol.* **2000**, *45*, 631–659. <https://doi.org/10.1146/ANNUREV.ENTO.45.1.631>
7. Allen, D. J. Pests, diseases, and nutritional disorders of the common bean in Africa: A field guide (No. 260). CIAT, Colombia, 1996; p.131
8. Otieno, M., Steffan-Dewenter, I., Potts, S. G., Kinuthia, W., Kasina, M. J., & Garratt, P. D. Enhancing legume crop pollination and natural pest regulation for improved food security in changing African landscapes. *Glob. Food Sec.* **2020**, *26*, 100394. <https://doi.org/10.1016/j.gfs.2020.100394>
9. Wortmann, C. S. Atlas of common bean (*Phaseolus vulgaris* L.) production in Africa (No. 297). CIAT, 1998.
10. Belmain, S. R., Neal, G., Ray, D. E., & Golob, P. Insecticidal and vertebrate toxicity associated with ethnobotanicals used as post-harvest protectants in Ghana. *Food Chem. Toxicol.* **2001**, *39*, 287–291. <https://doi.org/10.1016/S0278-6915%2800%2900134-4>
11. Mkenda, P. A., Ndakidemi, P. A., Stevenson, P. C., Sarah, S. E., Belmain, S. R., Chidege, M., & Gurr, G. M. Field margin vegetation in tropical African bean systems harbours diverse natural enemies for biological pest control in adjacent crops. *Sustainability.* **2019a**, *11*, 6399 <https://doi.org/10.3390/su11226399>
12. Mkenda, P. A., Ndakidemi, P. A., Stevenson, P. C., Arnold, S. E. J., Chidege, M., Gurr, G. M., & Belmain, S. R. Characterization of hymenopteran parasitoids of *Aphis fabae* in an African smallholder bean farming system through sequencing of coi ‘mini-barcode’. *Insects.* **2019b**, *10*, 331. <https://doi.org/10.3390/insects10100331>
13. Bale, J. S., Van Lenteren, J. C., & Bigler, F. Biological control and sustainable food production. *Philos. Trans. R. Soc. Lond., B, Biol. Sci.* **2008**, *363*, 761–776. <https://doi.org/10.1098/rstb.2007.2182>
14. Gurr, G.M, Reynolds, O.L, Johnson, A.C, Desneux, N, Zalucki, M.P, Furlong M.J, Li, Z.Y, Akutse, K.S, Chen, J.H, Gao, X.W, You, M.S. Landscape ecology and expanding range of biocontrol agent taxa enhance prospects for diamondback moth management. A review. *Agron. Sustain. Dev.* **2018**, *38*, 1–16. <https://doi.org/10.1007/s13593-018-0500-z>
15. Sampaio, M. V., Bueno, V. H. P., Silveira, L. C. P., & Auad, A. M. Biological control of insect pests in the tropics: In Tropical biology and conservation management, Del Claro K., Oliveira P.S., Rico-Gray V. Eds.; Eolss Publishers: Oxford, United Kingdom, 2009, pp. 28–70
16. Arnold, S. E. J., Elisante, F., Mkenda, P. A., Tembo, Y. L. B., Ndakidemi, P. A., Gurr, G. M., Darbyshire, I. A., Belmain, S. R., & Stevenson, P. C. Beneficial insects are associated with botanically rich margins with trees on small farms. *Sci. Rep.* **2021**, *11*, 1–11. <https://doi.org/10.1038/s41598-021-94536-3>
17. Kishinevsky, M., Keasar, T., & Bar-Massada, A. Parasitoid abundance on plants: effects of host abundance, plant species, and plant flowering state. *Arthropod-Plant Interact.* **2017**, *11*, 155–161. <https://doi.org/10.1007/s11829-016-9476-2>
18. Géneau, C. E., Wäckers, F. L., Luka, H., Daniel, C., & Balmer, O. Selective flowers to enhance biological control of cabbage pests by parasitoids. *Basic App Ecol.* **2012**, *13*, 85–93. <https://doi.org/10.1016/J.BAAE.2011.10.005>
19. Patt, J. M., Hamilton, G., & Lashomb, J. H. Impact of strip-insectary intercropping with flowers on conservation biological control of the Colorado potato beetle. *Adv. Hortic. Sci.* **1997**, *11*, 175–181.
20. Sivinski, J., Wahl, D., Holler, T., Al Dobai, S., & Sivinski, R. Conserving natural enemies with flowering plants: estimating floral attractiveness to parasitic Hymenoptera and attraction’s relationship to flower and plant morphology. *Biol. Control.* **2011**, *58*, 208–214. <https://doi.org/10.1016/J.BIOCONTROL.2011.05.002>
21. Tschumi, M., Albrecht, M., Entling, M. H., & Jacot, K. Targeted flower strips effectively promote natural enemies of aphids. *IOBCwprs Bull.* **2014**, *100*, 131–135. <https://doi.org/10.13140/2.1.4382.0488>
22. Wäckers FL and van Reijn PCJ, Pick and mix: selecting flowering plants to meet the requirements of target biological control insects, in Biodiversity and Insect Pests: Key Issues for Sustainable Management, Gurr, G.M., Wratten, S.D. and Snyder, W.E. Eds.; John Wiley & Sons Ltd., Chichester, UK, 2012; pp. 139–165
23. Fitzgerald, J. D., & Solomon, M. G. Can flowering plants enhance numbers of beneficial arthropods in U.K. apple and -pear orchards? *Biocontrol Sci. Technol.* **2004**, *14*, 291–300. <https://doi.org/10.1080/09583150410001665178>
24. Carrié, R. J., George, D. R., & Wäckers, F. L. Selection of floral resources to optimise conservation of agriculturally-functional insect groups. *J. Insect Conserv.* **2012**, *16*, 635–640. <https://doi.org/10.1007/s10841-012-9508-x>
25. Adda, C., Atachi, P., Hell, K., & Tamò, M. Potential use of the bushmint, *Hyptis suaveolens*, for the control of infestation by the pink stalk borer, *Sesamia calamistis* on maize in southern Benin, West Africa. *J. Insect Sci.* **2011**, *11*
26. Hillocks, R. J. The potential benefits of weeds with reference to smallholder agriculture in Africa. *J. Integr. Pest Manag.* **1998**, *3*, 155–167. <https://doi.org/10.1023/A:1009698717015>
27. Ojija, F., Arnold, S.E.J., Treydte, A.C. Impacts of alien invasive *Parthenium hysterophorus* on flower visitation by insects to co–Flowering plants. *Arthropod Plant Interact.* **2019**, *13*, 719–734. <https://doi.org/10.1007/s11829-019-09701-3>.
28. Bianchi, F.J.J.A. and van der Werf, W. Model evaluation of the function of prey in non-crop habitats for biological control by ladybeetles in agricultural landscapes. *Ecol. Model.* **2004**, *171*, 177–193. <https://doi.org/10.1016/J.ECOLMODEL.2003.08.003>
29. Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. Habitat management to suppress pest populations: progress and prospects. *Annu. Rev. Entomol.* **2017**, *62*, 91–109. <https://doi.org/10.1146/annurev-ento-031616-035050>
30. Jonsson, M., Wratten, S.D., Landis, D.A. and Gurr, G.M. Recent advances in conservation biological control of arthropods by arthropods. *Biol. Control.* **2008**, *45*, 172–175. <https://doi.org/10.1016/J.BIOCONTROL.2008.01.006>

31. Landis, D. A., Wratten, S. D., & Gurr, G. M. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology*, **2000**, *45*, 175–201. <https://doi.org/10.1146/ANNUREV.ENTO.45.1.175>
32. Lundgren, J. G. Nutritional aspects of non-prey foods in the life histories of predaceous Coccinellidae. *Biol. Control*. **2009**, *51*, 294–305. <https://doi.org/10.1016/J.BIOCONTROL.2009.05.016>
33. Mitsunaga, T., Shimoda, T. and Yano, E. Influence of food supply on longevity and parasitization ability of a larval endoparasitoid, *Cotesia plutellae* (Hymenoptera: Braconidae). *Appl. Entomol. Zool.* **2004**, *39*, 691–697. <https://doi.org/10.1303/AEZ.2004.691>
34. Tylianakis, J. M., Didham, R. K., & Wratten, S. D. Improved fitness of aphid parasitoids receiving resource subsidies. *Ecology*, **2004**, *85*, 658–666. <https://doi.org/10.1890/03-0222>
35. Wäckers, F.L., van Rijn, P.C.J., Bruin, J. (Eds.). *Plant-provided Food for Carnivorous Insects: A Protective Mutualism and its Applications*. Cambridge University Press, Cambridge, UK, 2005.
36. Patt, J. M. Occurrence of coccinellids that prey on *Diaphorina citri* (Hemiptera: Liviidae) on *Euphorbia heterophylla* (Euphorbiaceae) and *Chamaecrista fasciculata* (Fabaceae) in a South Florida Residential Area. *Fla. Entomol.* **2018**, *101*, 131–134. <https://doi.org/10.1653/024.101.0124>
37. Fonseca, M. M., Lima, E., Lemos, F., Venzon, M., & Janssen, A. Non-crop plant to attract and conserve an aphid predator (Coleoptera: Coccinellidae) in tomato. *Biol. Control*. **2017**, *115*, 129–134. <https://doi.org/10.1016/j.biocontrol.2017.10.005>
38. Grombone-Guaratini, M. T., Solferini, V. N., & Semir, J. Reproductive biology in species of *Bidens* L. (Asteraceae). *Sci. Agri*. **2004**, *61*, 185–189. <https://doi.org/10.1590/s0103-90162004000200010>
39. Quispe, R., Mazón, M., & Rodríguez-Berrío, A. Do refuge plants favour natural pest control in maize crops?. *Insects*. **2017**, *8*, 71. <https://doi.org/10.3390/insects8030071>
40. Shearer, P. W., & Atanassov, A. Impact of peach extrafloral nectar on key biological characteristics of *Trichogramma minutum* (Hymenoptera: Trichogrammatidae). *J. Econ. Entomol.* **2004**, *97*, 789–792. <https://doi.org/10.1093/jee/97.3.789>
41. Dufour, R. *Farmscaping to enhance biological control*. Fayetteville, AR: Appropriate Technology Transfer for Rural Areas. 2000; p 40
42. Gurr, G. M., Wratten, S. D., & Altieri, M. A. Ecological engineering: a new direction for agricultural pest management. *AFBM J*, **2004**, *1*, 28–35 <https://doi.org/10.22004/AG.ECON.120916>
43. Heimoana, V., Pilkington, L. J., Raman, A., Mitchell, A., Nicol, H. I., Johnson, A. C., & Gurr, G. M. Integrating spatially explicit molecular and ecological methods to explore the significance of non-crop vegetation to predators of brassica pests. *Agric. Ecosyst. Environ.* **2017**, *239*, 12–19. <https://doi.org/10.1016/j.agee.2017.01.008>
44. Jervis, M.A., Lee, J.C. and Heimpel, G.E. Use of behavioural and life history studies to understand the effects of habitat manipulation. *Ecological Engineering for Pest Management: In Advances in Habitat Manipulation for Arthropods*, Gurr, G.M., Wratten S.D. and Altieri M.A. Eds., CSIRO Publishing, Melbourne, 2004; pp. 65–100
45. Mitsunaga, T., Mukawa, S., Shimoda, T. and Suzuki, Y. The influence of food supply on the parasitoid against *Plutella xylostella* L. (Lepidoptera: Yponomeutidae) on the longevity and fecundity of the pea leafminer, *Chromatomyia horticola* (Goureaux) (Diptera: Agromyzidae). *Appl. Entomol. Zool.* **2006**, *41*, 277–285. <https://doi.org/10.1303/AEZ.2006.277>
46. Rahat, S., Gurr, G. M., Wratten, S. D., Mo, J., & Neeson, R. Effect of plant nectars on adult longevity of the stinkbug parasitoid, *Trissolcus basalus*. *Int. J. Pest Manag.* **2005**, *51*, 321–324. <https://doi.org/10.1080/09670870500312778>
47. Hogg, B.N., Bugg, R.L. and Daane, K.M. The attractiveness of common insectary and harvestable floral resources to beneficial insects. *Biol. Control*, **2011**, *56*, 76–84. <https://doi.org/10.1016/J.BIOCONTROL.2010.09.007>
48. Sutherland, J. P., Sullivan, M. S., & Poppy, G. M. (2001). Distribution and abundance of aphidophagous hoverflies (Diptera: Syrphidae) in wildflower patches and field margin habitats. *Agric. For. Entomol.* *3*, 57–64. <https://doi.org/10.1046/j.1461-9563.2001.00090.x>
49. Lu, Z. X., Zhu, P. Y., Gurr, G. M., Zheng, X. S., Read, D. M., Heong, K. L., Yang, Y.J & Xu, H. X. (2014). Mechanisms for flowering plants to benefit arthropod natural enemies of insect pests: prospects for enhanced use in agriculture. *Insect Sci.* **2014**, *21*, 1–12. <https://doi.org/10.1111/1744-7917.12000>
50. Charles, J. J., & Paine, T. D. Fitness effects of food resources on the polyphagous aphid parasitoid, *Aphidius colemani* Viereck (Hymenoptera: Braconidae: Aphidiinae). *PLoS ONE*, **2016**, *11*, 1–14. <https://doi.org/10.1371/journal.pone.0147551>
51. Idris, A. B., & Grafius, E. Wildflowers as nectar sources for *Diadegma insulare* (Hymenoptera: Ichneumonidae), a parasitoid of diamondback moth (Lepidoptera: Yponomeutidae). *Environ. Entomol.* **1995**, *24*, 1726–1735. <https://doi.org/10.1093/ee/24.6.1726>
52. Lee, J. C., & Heimpel, G. E. Floral resources impact the longevity and oviposition rate of a parasitoid in the field. *J. Anim. Ecol.* **2008**, *77*, 565–572. <https://doi.org/10.1111/j.1365-2656.2008.01355.x>
53. Munir, S., Dossall, L. M., & Keddie, A. Selective effects of floral food sources and honey on life-history traits of a pest–parasitoid system. *Entomol. Exp. Appl.* **2018**, *166*, 500–507. <https://doi.org/10.1111/eea.12695>
54. Díaz-Castelazo, C., Rico-Gray, V., Oliveira, P. S., & Cuautle, M. Extrafloral nectary-mediated ant-plant interactions in the coastal vegetation of Veracruz, Mexico: Richness, occurrence, seasonality, and ant foraging patterns. *Ecoscience*, **2004**, *11*, 472–481. <https://doi.org/10.1080/11956860.2004.11682857>
55. Hernandez, L. M., Otero, J. T., & Manzano, M. R. Biological control of the greenhouse whitefly by *Amitus fuscipennis*: Understanding the role of extrafloral nectaries from crop and noncrop vegetation. *Biol. Control*, **2013**, *67*, 227–234. <https://doi.org/10.1016/j.biocontrol.2013.08.003>
56. Koptur, S., William, P., & Olive, Z. Ants and plants with extrafloral nectaries in fire successional habitats on Andros (Bahamas). *Fla. Entomol.* **2010**, *93*, 89–99. <https://doi.org/10.1653/024.093.0112>

57. Mizell, R.F. (2001). Many plants have extrafloral nectaries helpful to beneficials. University of Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, EDIS, Florida, USA: 2001, <http://edis.ifas.ufl.edu/in175>
58. Patt, J. M., & Rohrig, E. Laboratory evaluations of the foraging success of *Tamarixia radiata* (Hymenoptera: Eulophidae) on flowers and extrafloral nectaries: potential use of nectar plants for conservation biological control of Asian citrus psyllid (Hemiptera: Liviidae). *Fla. Entomol.* **2017**, *100*, 149-156. <https://doi.org/10.1653/024.100.0121>
59. González-Teuber, M., & Heil, M. Nectar chemistry is tailored for both attractions of mutualists and protection from exploiters. *Plant Signal. Behav.* **2009**, *4*, 809–813. <https://doi.org/10.4161/psb.4.9.9393>
60. Wäckers, F. L., Van Rijn, P. C., & Heimpel, G. E. Honeydew as a food source for natural enemies: making the best of a bad meal?. *Biol. Control.* **2008**, *45*, 176-184. <https://doi.org/10.1016/J.BIOCONTROL.2008.01.007>
61. Zhu, P., Lu, Z., Heong, K., Chen, G., Zheng, X., Xu, H., Yang, Y., Nicol, H. I., & Gurr, G. M. Selection of nectar plants for use in ecological engineering to promote biological control of rice pests by the predatory bug, *Cyrtorhinus lividipennis*, (Heteroptera: Miridae). *PLoS ONE.* **2014**, *9*, 1–12. <https://doi.org/10.1371/journal.pone.0108669>
62. Fernandez, C., & Nentwig, W. Quality control of the parasitoid *Aphidius colemani* (Hym., Aphidiidae) used for biological control in greenhouses. *J. Appl. Entomol.* **1997**, *121*, 447-456. <https://doi.org/10.1111/j.1439-0418.1997.tb01433.x>
63. Starý, P. Field establishment of *Aphidius colemani* Vier.(Hym., Braconidae, Aphidiinae) in the Czech Republic. *J. Appl. Entomol.* **2002**, *126*, 405-408. <https://doi.org/10.1046/J.1439-0418.2002.00663.X>
64. Adisu, B., Starý, P., Freier, B., & Büttner, C. *Aphidius colemani* Vier.(Hymenoptera, Braconidae, Aphidiinae) detected in cereal fields in Germany. *Anzeiger für Schädlingskunde= J. Pest Sci.* **2002**, *75*, 89-94.
65. Dannon, E. A., Tamò, M., Van Huis, A., & Dicke, M. Effects of volatiles from *Maruca vitrata* larvae and caterpillar-infested flowers of their host plant *Vigna unguiculata* on the foraging behavior of the parasitoid *Apanteles taragamae*. *J. Chem. Ecol.* **2010**, *36*, 1083–1091. <https://doi.org/10.1007/s10886-010-9859-2>
66. Yogesh, W.H., Deepali G. M. & Sagar, B. P. Larvicidal effects of *Parthenium hysterophorus* against polyphagous pests *Spodoptera litura* and *Spodoptera littoralis*. *Indian J. Appl. Res.* **2019**, *2*, 18–19.
67. Dormann, C.F., Fruend, J., Bluethgen, N. & Gruber B. Indices, graphs and null models: analyzing bipartite ecological networks. *Open J. Ecol.* **2009**, *2*, 7-24. <https://doi.org/10.2174/1874213000902010007>
68. Russell Lenth. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.4.1. 2019. <https://CRAN.R-project.org/package=emmeans>
69. Kassambara, A., Kosinski, M., Biecek, P., & Fabian, S. Package ‘survminer’. Drawing Survival Curves using ‘ggplot2’ (R package version 0.4.9), 2017. <https://CRAN.R-project.org/package=survminer>
70. Koptur, S. Nectar as fuel for plant protectors. Plant-provided food for carnivorous insects: a protective mutualism and its applications. Cambridge University Press: Cambridge, UK, 2005; pp. 75-108
71. Patel, S. Harmful and beneficial aspects of *Parthenium hysterophorus*: an update. *3 Biotech*, **2011**, *1*, 1–9. <https://doi.org/10.1007/s13205-011-0007-7>
72. Ramos, A., Rivero, R., Visozo, A., Piloto, J., & García, A. Parthenin, a sesquiterpene lactone of *Parthenium hysterophorus* L. is a high toxicity clastogen. *Mutat. Res. Genet. Toxicol. Environ. Mutagen.* **2002**, *514*, 19-27.