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Semiochemically assisted trap cropping to reduce broad bean beetle (*Bruchus rufimanus*) infestation in faba bean

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ABSTRACT

Damaged beans and adults of broad bean beetles (*Bruchus rufimanus*) in harvested beans are currently a bottleneck for faba bean production, especially for human consumption. The availability and efficiency of insecticides to control broad bean beetles are limited. We tested trap cropping combined with semiochemical trapping as an alternative pest management strategy. A field experiment was performed in south central Sweden over two years, in 2021 and 2023, in a total of 24 faba bean fields. Fields were paired, such that each pair ($n = 12$) contained one treated field with a perimeter strip of an early flowering faba bean cultivar used as a trap crop in combination with semiochemical traps, and one control field with just the faba bean main crop without a trap crop or semiochemical traps. Eggs per pod and proportion of beans with emergence holes were 147 % and 73 % higher in the trap crop strip in treated fields compared to the corresponding area grown with the main crop cultivar in control fields. Eggs per pod and proportion beans with emergence holes were conversely 28 % and 18 % lower respectively, in the main crop in fields with trap crops compared to control fields, but only in the field centers and not the field edges. Yield of the main crop was not affected by semiochemically assisted trap cropping. Overall the trap crop treatment successfully reduced damage by broad bean beetles but only modestly so. Further development of the trap cropping strategy might, however, be able to contribute to satisfactory broad bean beetle control.

1. Introduction

Pests, pathogens and weeds cause substantial economic losses to crop production (Oerke, 2006, Savary et al., 2019). Pesticides have successfully been able to limit such losses, but are increasingly being scrutinized due to their negative effects on biodiversity, the environment and concerns for human health (Oerke, 2006, Geiger et al., 2010, Popp et al., 2013, Jacquet et al., 2022, Frank, 2024). Consequently, policies for reducing the use and impact of pesticides have emerged in Europe (Lee et al., 2019, European Commission, 2020). Furthermore, a lack of discovery of new modes of actions, increasing costs for registrations and pesticide resistance development (Duke, 2012, Hawkins et al., 2019) also limit the prospects for relying on chemical pesticides for pest control. Alternative strategies for crop protection are thus urgently needed (Deguine et al., 2021, Jacquet et al., 2022, Bommarco, 2024).

Faba bean (*Vicia faba* L.) is an important grain legume crop grown worldwide (Jensen et al., 2010, Karkanis et al., 2018). Local production and inclusion of faba bean and other grain legumes in cropping systems are associated with several agronomic and environmental benefits (Köpke and Nemecek, 2010). Importantly, faba bean plants have a high efficiency to fix atmospheric nitrogen, which can reduce reliance on nitrogen fertilizers, and their beans a high protein content, which can increase plant protein self-sufficiency and replace imported soybeans in animal feed (Köpke and Nemecek, 2010, Nordborg et al., 2017). Nonetheless, faba bean and other grain legumes are currently grown on less than 3 % of arable land in Europe due to agronomic and economic constraints (Notz et al., 2023). Additional environmental benefits would be realized if locally produced grain legumes in Europe to a larger extent were produced for direct human consumption rather than primarily for feed, as is currently the case (Röös et al., 2020).

Crop protection against weeds, diseases and insect pests is one of the factors hampering faba bean production (Stoddard et al., 2010). Among insect pests, damage by the broad bean beetle (*Bruchus rufimanus* Boh.) has emerged as a major issue in Europe (Roubinet, 2016, Segers et al.,

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2021). Broad bean beetle adults colonize faba bean fields, where they feed on pollen and nectar, and lay their eggs on the developing pods (Pölitz and Reike, 2019, Hamidi et al., 2021). Crop damage is done by the larvae as they bore into, feed and develop inside the beans (Roubinet, 2016). The beetles either emerge from the beans prior to harvesting to overwinter in the surrounding landscape, or overwinter inside the beans in storage facilities (Segers et al., 2021). While broad bean beetle damage has less consequences for crop yield when faba bean is grown for animal feed, it is detrimental for seed production quality. This is because damage to seeds leads to reduced germination and shoot vigor, especially in combination with seed-borne fungal pathogens (Khelfane-Goucem and Medjdoub-Bensaad, 2016, Almogdad et al., 2023, Huber et al., 2023). In the case of faba bean for human consumption, damage by broad bean beetles becomes a critical issue due to the aesthetic of the damaged beans and substantial presence of remaining insects in the harvested product (Segers et al., 2021). Currently there are no effective chemical or alternative control methods available for broad bean beetle in faba bean (Roubinet, 2016, Segers et al., 2021). As such, the broad bean beetle presents a major obstacle for increased grain legume production for human consumption in Europe.

Trap crops are “plant stands that are, per se or via manipulation, deployed to attract, divert, intercept, and/or retain targeted insects or the pathogens they vector in order to reduce damage to the main crop” (Shelton and Badenes-Perez, 2006), and they have been applied successfully in a number of cases against various insect pests (Hokkanen, 1991, Shelton and Badenes-Perez, 2006). Since early flowering accessions of faba bean are more damaged by broad bean beetles than later flowering accessions (Dell’Aglio and Tayeh, 2023, Ohm et al., 2024), an earlier flowering cultivar might be able to act as a trap crop to protect a field with a later flowering main cultivar from broad bean beetles, when grown together. One potential issue with a trap crop based on phenological differences in attractiveness to the insect pest is that while the early flowering cultivar initially could be more attractive, insects might eventually disperse and also damage the later flowering main cultivar. The effectiveness of a trap cropping system is thus generally improved by combining the trap crop with a control agent, which kills the insect pest before it can disperse into the main crop, or by further enhancing the trap crop attractiveness using semiochemicals (Shelton and Badenes-Perez, 2006, Holden et al., 2012).

Semiochemicals are chemicals used for signaling between individuals of the same species (pheromones) or among different species (kairomones) to modify the behavior of the recipient (Cook et al., 2007). Kairomones in the form of flower and pod scents that are attractive to broad bean beetles have been identified and their efficacy as lures for both monitoring and mass trapping has been evaluated considering crop phenology and different trap designs (Bruce et al., 2011, Segers et al., 2021, Segers et al., 2023). While the idea of combining a trap crop with semiochemicals is not new (Shelton and Badenes-Perez, 2006), large-scale evaluations of its performance have to our knowledge rarely been done for any crop-insect pest system (but see Thöming et al., 2020 for an application in oilseed rape).

Here, our aim was to evaluate a semiochemically assisted trap cropping treatment for broad bean beetle control in faba bean production, where we combined an earlier flowering faba bean cultivar as a trap crop with kairomone traps placed in the trap crop as a mass trapping agent. To optimize the effectiveness of the kairomone traps in the trap crop, flower and pod kairomones were deployed earlier compared to when these scents are emitted by the trap crop. We expected that oviposition and damage to beans by broad bean beetles would be higher in the trap crop compared to the main faba bean crop, and that consequently the main crop of treated fields would have fewer eggs on pods and less damage to beans compared to control fields without a semiochemically assisted trap crop. The number of broad bean beetles caught in traps baited with semiochemicals in the trap crops was counted weekly, and their sex determined in order to evaluate the effectiveness of the mass trapping. We also measured yield and its components in both the trap and main crop, as this would be an important factor to consider in the potential application of this pest management strategy.

2. Material and methods

2.1. Study design

We set up a landscape scale experiment with a total of 24 commercially grown faba bean fields in 2021 (n = 10) and 2023 (n = 14) in the region of Östergötland in south-central Sweden (Table 1, Fig. 1a). None of the fields included in 2021 were included again in 2023. The fields were situated in landscapes dominated by agriculture with embedded forest fragments. Winter wheat, spring barley and winter oilseed rape were common crops grown. A majority of the fields were organically managed and no insecticides were used in the conventionally managed fields. The fields were organized in 12 field pairs, with one treated and one control field in each pair. Fields within pairs were managed by the same farmer and were located at least 10 m and at most 550 m apart, with one exception where the fields within a pair were managed by two different farmers and 6 km apart. As the fields that were 6 km apart also were part of the only pair that differed in farming practice (conventional versus organic), we tested to exclude this field pair from the analyses. Doing so did not alter any conclusions and therefore we decided to keep this field pair in the analysis. The minimum distance between fields belonging to different pairs in the same year was 6 km, and the maximum was 93 km. Sowing dates and cultivars were balanced within the field pairs, with one exception in 2021, where the cultivar of the main crop differed between the fields in the field pair. Because the cultivars in this field pair, Fuego and Fanfare, have similar properties and susceptibility to broad bean beetle (Ohm et al., 2024) we decided to include this field pair in the analysis. The larger field within each pair was interchangeably assigned to the semiochemically assisted trap crop and control treatment, respectively, in order to avoid any bias in field size among the treatments (Table 1).

We established three transects in each field, which all were in parallel to the field border and continued all the way around the field (Fig. 1b), and from which all measurements were taken. The first transect, henceforth referred to as strip, was in the center of the trap crop in treated fields, that is 4–8 m from the field edge depending on the trap crop width, or in control fields, at the same distance as the strip transect in the treated field within that pair. In control fields, the cultivar in the strip was the same as in the main crop. The second transect, henceforth referred to as edge, was 5 m into the main crop from the trap crop in treated fields, that is 13–21 m from the field edge depending on the trap crop width, or in control fields, at the same distance from the field edge as the edge transect in the treated field within that pair. The third transect, henceforth referred to as center, was 30 m into the main crop from the trap crop in treated fields, that is 38–46 m from the field edge depending on the trap crop width, or in control fields, at the same distance from the field edge as the center transect in the treated field within that pair. Thirty meters was chosen for the center transect as it was the maximum distance we could move into the main crop from all field sides in all fields.

2.2. Trap crop

The trap crop consisted of a strip of the early flowering Finnish faba bean cultivar Sampo (Boreal Plant Breeding Ltd, Jokioinen, Finland), which starts flowering approximately one week before faba bean cultivars commonly grown in Sweden (Ohm et al., 2024). The trap crop in the strip of treated fields was sown by the farmers on the same day as the rest of the field along the entire perimeter of the field. The width of the strip was typically 12 m, but was adapted to the sowing machinery available to each farmer and therefore varied between 8 and 16 m (Table 1). Depending on strip width as well as field size and geometry, the trap crop proportion was on average approximately 25 % (range

Table 1
Characteristics for each field included in the experiment: year, field pair identity (ID, 1–12), treatment (trap crop or control), field size (hectares), sowing date, cultivar, whether or not the field was organically managed and the distance between fields in each pair (m). For fields with trap crops also the width of the trap crop (m) and the number (#) of semiochemical traps deployed.

Year	Pair ID	Treatment	Field size (ha)	Sowing date	Cultivar	Organic	Field pair distance (m)	Trap crop width (m)	# Traps
2021	1	Trap crop	3,4	26-Apr	Fanfare	Yes	130	12	44
	1	Control	2,1	26-Apr	Fuego	Yes			
	2	Trap crop	3,4	11-Apr	Stella	Yes	12	12	35
	2	Control	7	11-Apr	Stella	Yes			
	3	Trap crop	4	19-Apr	Fanfare	No	6000	12	43
	3	Control	2,5	20-Apr	Fanfare	Yes			
	4	Trap crop	4,2	27-Apr	Aurora	Yes	15	16	47
	4	Control	11	27-Apr	Aurora	Yes			
	5	Trap crop	4,1	29-Apr	Paloma	Yes	165	12	53
	5	Control	9	29-Apr	Paloma	Yes			
2023	6	Trap crop	6	07-May	Aurora	Yes	150	9	52
	6	Control	5,5	07-May	Aurora	Yes			
	7	Trap crop	6	10-May	Aurora	Yes	100	9	45
	7	Control	12,5	10-May	Aurora	Yes			
	8	Trap crop	8	29-Apr	Fuego	Yes	550	12	56
	8	Control	9,3	29-Apr	Fuego	Yes			
	9	Trap crop	10	30-Apr	Tiffany	No	50	12	64
	9	Control	2,5	30-Apr	Tiffany	No			
	10	Trap crop	7	22-Apr	Birgit	Yes	10	12	52
	10	Control	5	22-Apr	Birgit	Yes			
	11	Trap crop	2,2	01-May	Birgit	Yes	10	8	45
	11	Control	5,6	01-May	Birgit	Yes			
	12	Trap crop	3	30-Apr	Boxer	No	50	12	38
	12	Control	3	30-Apr	Boxer	No			

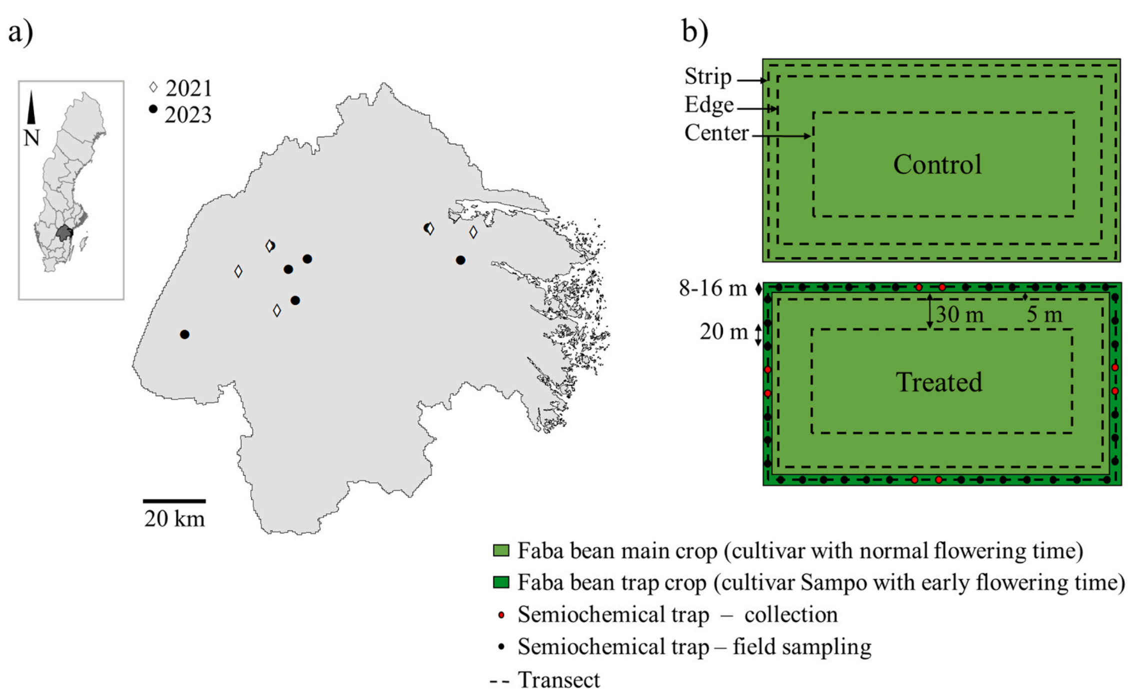

Fig. 1. (a) Field pair locations in Östergötland, Sweden (inset), where the treated field in each pair is indicated with a white diamond (2021) or black circle (2023) depending on the year of sampling, (b) schematic illustration of the control and treated fields in a field pair showing the faba bean main crop (light green), faba bean trap crop (dark green), semiochemical traps (red dots indicate traps that were collected to sex beetles and black dots indicate traps sampled in the field), and sampling transects (dashed lines). Note that in the control field, strip and main crop consist of the same cultivar. Control fields are not shown in (a) because in most cases they are close to the treated field (Table 1) and would thus not be clearly visible in the map at this scale.

15–35 %) of the total field area in treated fields.

2.3. *Semiochemical traps*

The trap crop was combined with semiochemical traps commercialized by Agriodor (Rennes, France) to enhance the trap crops' attractiveness for broad bean beetles and to trap and kill the beetles so that they do not disperse into the main crop. Semiochemical traps were placed every 20 m in the strip transect only in treated fields with trap crops (Fig. 1b), resulting in 35–64 semiochemical traps per field depending on field perimeter length (Table 1). The semiochemical traps were activated from the bud stage (BBCH 50, Lancashire et al., 1991, June 4–13) until the end of the pod formation stage 6–7 weeks later (BBCH 79, July 17–25). Two kairomonal attractants were used: one with faba bean flower and one with faba bean pod scent. The flower scent was composed of (R)- linalool (94 %), cinnamyl alcohol (2 %) and cinnamaldehyde (4 %) (Bruce et al., 2011). The pod scent was composed of cis-3-hexenyl acetate (30–40 %), ocimene (15–20 %), linalool (10–20 %), beta-caryophyllene (10–20 %) and limonene (15–20 %) (Segers et al., 2023, Ené Leppik, personal communication).

The kairomonal attractants were contained in Eppendorf tubes that were placed in the center of the traps (Fig. 2). While the kairomones used were identical in both years, we used different trap types holding the dispensers in 2021 and 2023. In 2021, we used pan traps (12 cm diameter) filled with water and scentless detergent to reduce surface tension, while in 2023 we used white double-sided sticky traps (25 by 16 cm sticky trap area on each side. Fig. 2). The change of trap type between years was because the water traps used in 2021 needed to be re-filled twice per week during warm and dry weather, making them labor-intensive and more difficult to manage compared to the sticky traps. The sticky traps were replaced once during the season, after 3 weeks. For the first 2–3 weeks during the bud and flowering stage of the crop, every second trap was loaded with flower scent and every other trap with pod scent. When pods began to form in the second half of flowering (BBCH 65–69), all dispensers were replaced to exclusively contain pod scents that were active for the last 3–4 weeks of the trapping duration. We counted the number of broad bean beetles trapped weekly and emptied and re-filled the water traps in 2021, or marked caught beetles with nail polish in the sticky traps in 2023 in order to keep track of the number of individual beetles caught weekly.

In a subset of eight semiochemical traps in each field, situated in pairs along each of the four field edge directions (Fig. 1b), we identified and counted male and female broad bean beetles that were trapped. In the case of two triangular fields, beetles were identified to sex only in six semiochemical traps. One trap in each pair had flower and one bud scent in the first period of sampling, until scents were replaced with pod scents in all traps. The sex identification was based on the presence of a spur on the middle leg in males, which is missing in females (Segers et al., 2021).

2.4. Broad bean beetle eggs on pods

We counted the number of broad bean beetle eggs on 50 pods from each transect in each field when it had reached approximately crop stage BBCH 75 (50 % of pods have reached full length) between 7 and 18 July. Each pod was collected from a separate randomly selected plant along the transect. Every third pod was collected from the bottom, middle or top part of the plant, respectively.

2.5. Broad bean beetle damage to beans and crop yield components

We collected approximately 90 pods (range 70–118) from each transect at crop maturity (BBCH 89) soon before commercial crop harvest by the farmers. Every pod came from a different randomly selected plant along the transect and we interchangeably picked pods that were positioned at the bottom, center and top of the plant. At the same time or shortly before we also counted the number of faba bean plants in four 1 by 1 m quadrats in each transect, and the number of pods with beans on 10 randomly selected plants per transect.

The pod samples were kept in paper bags in ambient temperature in a room with daylight for at least one month before processing to promote broad bean beetle emergence. Pods were subsequently oven-dried for 48 h at 65 degrees C. We then opened the pods, counted and weighed all beans and counted damaged beans with characteristic broad bean beetle emergence holes. From this data, we divided the number of beans with the number of pods to calculate beans per pod and divided the weight with the number of beans to calculate weight per bean. Finally, we produced an estimate of the crop yield for each transect by multiplying average number of plants per square meter, pods per plant, beans per pod and weight per bean. Data on pods per plant was missing from one field pair in 2021, and data on beans per pod was also missing for one field in the same pair.

2.6. Statistical analyzes

Statistical analyzes were done using (generalized) linear mixed effects models in R version 4.4.1 for Windows (R Core Team, 2024). Linear mixed effect models were analyzed with the *lmer* function and generalized linear models with the *glmer* function (package: *lme4*, Bates et al., 2015). The amount of variances that contributed to a sample by the explanatory variables was analyzed with a type 2 ANOVA (package: *car*, Fox and Weisberg, 2019). As explanatory variables, all models included the two-way interaction of treatment (semiochemically assisted trap crop or control) and transect (strip, edge or center), as well as the main effect of year (2021, 2023). We did not simplify models because

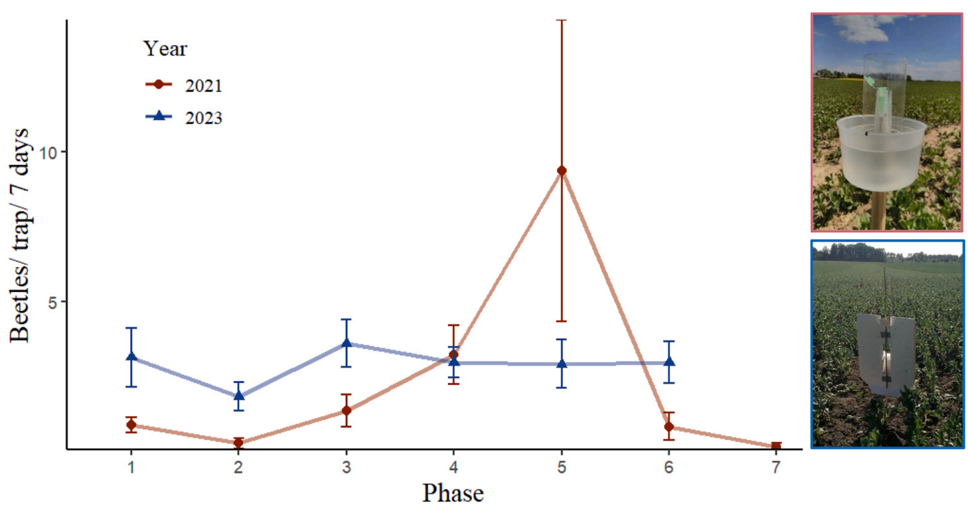

Fig. 2. Weekly semiochemical trap catches (average number of *Bruchus rufimanus* beetles per trap and seven days) in 2021 (red line and circles) and 2023 (blue line and triangles) depending on the crop growth phase (1 = bud stage, 2 = early flower stage, 3 = mid flower stage, 4 = late flower stage, 5 = early pod stage, 6 = mid pod stage and 7 = late pod stage. Error bars show standard errors. Scents were replaced from a mix of flower and pod scents into only pod scents after stage 3, as the first pods start to form in the later parts of the flowering stage. Semiochemicals used were: flower scent: (R)- linalool (94 %), cinnamyl alcohol (2 %) and cinnamaldehyde (4 %); pod scent: cis-3-hexenyl acetate (30–40 %), ocimene (15–20 %), linalool (10–20 %), beta-caryophyllene (10–20 %) and limonene (15–20 %). Photos to the right show the trap types used for 2021 (top) and 2023 (bottom).

treatment by transect interactions were an inherent part of the experimental design. Due to limited sample size we did not include any interactions with year in the models. We visually examined that models were not over- or under-dispersed and that model assumptions were met using the *simulateResidual* and *testDispersion* functions (package: *DHARMa*, Hartig, 2022). We computed the marginal and conditional R^2 values of our models using the *r2_nakagawa* function (package: *performance*, Lüdecke et al., 2021) according to Nakagawa et al. (2017). To evaluate significant interactions between treatment and transect, we performed post-hoc tests using the *emmeans* function (package: *emmeans*, Lenth, 2023), where the treatment effect (treatment or control) was evaluated separately for each transect type (strip, edge or center). We plotted the results with *ggplot* (package: *ggplot2*, Wickham, 2016).

To analyze if the number of eggs per pod differed among treatment and transect combinations, we used the number of eggs per pod as the response variable, and a generalized linear model with a negative binomial distribution with a log link. As random effect we included transect nested within treatment and field pair identity (1| Field_ID/treatment/transect). Transect was included in the random structure to account for repeated sampling on 50 pods within each transect.

To analyze if the proportion of damaged beans differed among treatment and transect combinations, we calculated the total number of beans and the number of damaged beans per transect. We then used a generalized linear mixed effects model with a binomial distribution with a logit link and included treatment nested within field pair identity as a random effect (1| Field_ID/treatment).

Crop yield, which was estimated using bean weight per square meter as the response variable, was analyzed using a linear mixed effects model with a normal distribution and included treatment nested within field pair identity as a random effect (1| Field_ID/treatment).

To analyze if the number of plants per square meter and yield components differed among transect and treatment combinations, we used plants per square meter, pods per plant, and the average number of beans per pod and individual bean weight as response variables. For the models to analyze plants per square meter and pods per plant, we used generalized linear mixed effects model with a negative binomial distribution and a log link, and included transect nested within treatment and field pair identity (1| Field_ID/treatment/transect) as random effects. Transect was included in the random structure to account for repeated sampling of plants in four quadrats and pods on 10 plants within each transect. For the models to analyze the average number of beans per pod and individual bean weight, we used linear mixed effects models with a normal distribution and included treatment nested within field pair identity as random effects (1| Field_ID/treatment).

3. Results

3.1. *Bruchus rufimanus* adults in semiochemical traps

A total of 9640 broad bean beetles were caught in the semiochemical traps in the trap crop strip in treated fields, with similar number of individuals per trap and day in both years (Fig. 2). In 2021, there was a peak in the middle of the pod formation stage, whereas catches were more evenly distributed in 2023 (Fig. 2). On the first set of scents applied during the bud and flowering stages, 56 % of the individuals collected with flower scents and 60 % of the individuals collected with pod scents, respectively were females. On the second set of scents applied during pod formation, 82 % of the individuals collected with the pod scents were females.

3.2. Broad bean beetle eggs on pods

The number of broad bean beetle eggs on pods was explained by an interaction between the treatment and transect (Table 2). Post-hoc tests showed that the number of eggs on pods were higher in the trap crop strips of treated fields compared to the strip in control fields, but lower in the center of treated fields compared to the center of control fields (Fig. 3a). There were no differences in the number of eggs per pod between the edges of treated and control fields (Fig. 3a).

Table 2
Statistical test results for the effect of treatment (trap crop or control), transect (strip, edge or center), year (2021 or 2023) as well as the interaction between treatment and transect on the number of broad bean beetle eggs per pod, the proportion of damaged beans and crop yield (bean mass per square meter). Shown for each tested variable are the test statistics (Chi-square or F-value), degrees of freedom (DF), residual DF and p-values (P). For each model we also provide the model distribution and the marginal (Rm) and conditional (Rc) R^2 values. Statistically significant ($p < 0.05$) results are indicated in bold.

Variable					Model distribution
eggs	Rm= 0.16	Rc= 0.59			negative binomial
	Chi Sq	**DF**		**P**	
Treatment	1.09	1		0.30	
Transect	**37.45**	**2**		**< 0.001**	
Year	1.03	1		0.31	
Treatment*Transect	**53.78**	**2**		**< 0.001**	
bean damage	Rm= 0.28	Rc= 0.99			binomial
	Chi Sq	**DF**		**P**	
Treatment	2.06	1		0.15	
Transect	**394.68**	**2**		**< 0.001**	
Year	0.019	1		0.89	
Treatment*Transect	**420.85**	**2**		**< 0.001**	
yield	Rm= 0.47	Rc= 0.65			normal
	F	**DF**	**DF. res**	**P**	
Treatment	0.69	1	10	0.42	
Transect	**21.96**	**2**	**40**	**< 0.001**	
Year	**6.76**	**1**	**9**	**0.029**	
Treatment*Transect	**8.0**	**2**	**40**	**0.0012**	

3.3. Proportion of beans damaged by broad bean beetle

The proportion of beans with broad bean beetle emergence holes was also explained by an interaction between the treatment and transect (Table 2). Post-hoc tests showed that the proportion of beans with broad bean beetle damage was higher in the trap crop strips of treated fields compared to the strips of control fields, but lower in the centers of treated fields compared to the centers of control fields (Fig. 3b). The proportion of beans with broad bean beetle damage also tended to be lower in the edges of treated fields compared to the edges of control fields (Fig. 3b).

3.4. Faba bean yield

Bean mass per square meter was also explained by an interaction between the treatment and transect (Table 2). Posthoc tests showed that the bean mass per square meter was lower in the strips of the treated fields compared to the strips of control fields, whereas it did not differ between treated and control fields in the edge or center transects of the main faba bean crop (Fig. 3c). Bean mass per square meter was in addition 59 % higher in 2023 compared to 2021 (Table 2).

Analyses of the components of the faba bean yield are reported in Fig. S1 and Table S1. The number of faba bean plants per square meter was higher in treated compared to control fields (Fig. S1a), and there were also 38 % more plants per square meter in 2023 compared to 2021 (Table S1). The number of pods per plant were lower in treated fields compared to control fields, but only in the strips and not in the field edges or centers (Fig. S1b). The number of beans per pod was lower in the strip compared to the edge and center transects independent of the treatment (Fig. S1c), and there were 13 % more beans per pod in 2023 compared to 2021 (Table S1). The weight per bean was lower in treated

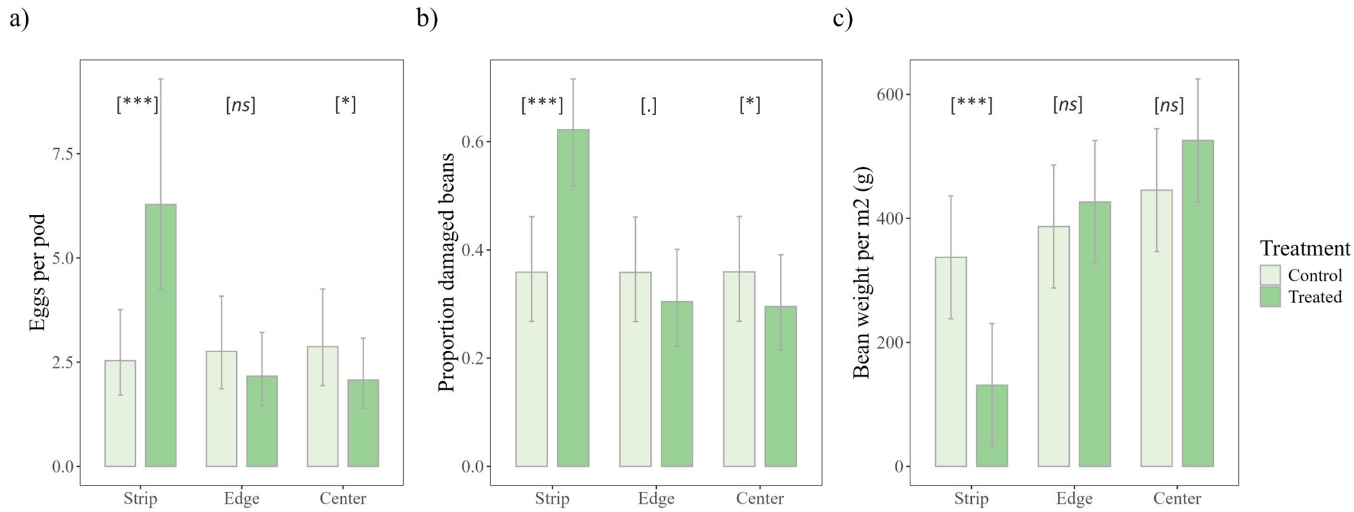

Fig. 3. a) Number of broad bean beetle eggs per pod, b) proportion of damaged beans, and c) bean weight per square meter in the strip, edge and center of treated fields (dark green) with a semiochemically assisted trap crop or control fields (light green). The strip in the treated field was cultivated with an early-flowering cultivar. Shown are estimated means averaged across 2021 and 2023, combined with 95 % confidence intervals. Alpha levels of pair-wise comparisons of the estimated marginal means of post-hoc tests are indicated by *** < 0.001, * < 0.050, · < 0.10 and ns ≥ 0.10.

fields compared to control fields, but only in the strips and not in the field edges of centers (Fig. S1d), and beans were also 27 % lighter in 2023 compared to 2021 (Table S1).

4. Discussion

Overall the semiochemically assisted trap cropping strategy showed promising results with statistically significant but yet modest reductions of damage to beans (-18 % in the field center) in fields with a trap crop compared to control fields. As such, the field experiments provided a proof-of-concept, but also led to further questions of how the cost-benefit ratio of the pest management strategy can be improved further and become more practical for use by farmers.

In fields with semiochemically assisted trap crops, eggs per pod and the proportion of damaged beans was higher in the trap crop strip that was cultivated with the early-flowering cultivar Sampo, compared to in the strips of the control fields that was cultivated with the same cultivar as the main faba bean crop. In field centers, the opposite pattern was found, with fewer eggs per pod and a lower proportion of damaged beans in treated fields with a trap crop strip compared to control fields, and there was a similar trend in edges closer to the strips. The somewhat less strong effect at the edges could have been caused by spillover of broad bean beetles from the trap crop to the main crop edge. The trap crop strips likely attracted adult broad bean beetles early in the season, especially when the trap crop but not yet the main crop was flowering, providing nectar and pollen for feeding, and later for oviposition when pods where present in the trap crops but not yet the main crops (Hamidi et al., 2021, Gailis et al., 2022).

The direct impact of broad bean beetle on faba bean crop yield is limited as the larvae only consume a fraction of the bean (Segers et al., 2021, Riggi et al., 2022, Huber et al., 2023), and consequently yield of the main crop was not affected by the trap cropping treatment. The yield of the trap crop itself was lower compared to the control strips that consisted of various commercial cultivars that are commonly grown in Sweden. The difference in yield was mainly driven by the small size and low weight per bean, which is a known trait of the trap crop cultivar, Sampo (Ohm et al., 2024). The higher plant density in treated fields was likely also driven by the trap crop as the farmers in several cases chose to sow the trap crop more dense compared to the main crop due to e.g., the smaller plant size of the trap crop cultivar. One possible usage for the trap crop, which at the same time might assist in regulating the broad bean beetle population for the coming season by preventing beetle reproduction, is to harvest the trap crop early, at around 70 % dry matter, and use it for animal feed as silage (Bachmann et al., 2020).

Further development of the trap cropping strategy might be able to increase its effectiveness, which also would be needed for the economic benefits to outweigh costs. We took advantage of the fact that early flowering cultivars attract the broad bean beetle (Seidenglanz and Huňady, 2016, Dell'Aglio and Tayeh, 2023, Ohm et al., 2024), but the differences in initiation in flowering is restricted to around one week for commercially available spring faba bean cultivars when sown at the same time. There is also convincing evidence that broad bean beetle attractiveness and damage differs with sowing date within a cultivar, with a later sowing receiving less damage (Szafirowska, 2012, Ward, 2018, Carrillo-Perdomo et al., 2019, Dell'Aglio and Tayeh, 2023). One way to further increase the phenological difference between the trap and main crop, and possibly increase the strategy's effectiveness, is thus to delay the sowing of the main crop relative to the trap crop. Other *Vicia* or *Lathyrus* host plant species for broad bean beetle (Kergoat et al., 2007, Kabott et al., 2024) could also be tested as alternative trap crops. A complementary strategy is also to reduce the main crops' attractiveness for example by intercropping the main faba bean crop with another crop, which either impedes host localization in beetles or deters them (see Poveda et al., 2008). The trap crops occupied a substantial proportion (on average 25 %) of the faba bean fields and it could be worth exploring if reducing this proportion is possible without compromising trapping effectiveness. In general, however, the trap crop proportion is expected to be positively related to the pest control effectiveness (Banks and Ekbom, 1999).

One additional factor that probably limited the effect of the trap cropping strategy in our case and thus has room for improvement, is low retention of broad bean beetles in the trap crop. Beetles caught in the semiochemical traps were primarily females, especially on the pod scents and later in the season, which is in line with the species' biology, with females locating oviposition sites during the pod stage (Segers et al., 2023). The number of beetles caught in the semiochemical traps were, however, too low to cause a mass-trapping effect (see calculation in Text S1), but we cannot rule out that the semiochemical traps nonetheless increased the attractiveness of the trap crop. Further testing of trap crops with and without semiochemical traps would be needed to conclusively determine their relative contribution to pest control. As the flower and pod kairomones were deployed in the semiochemical traps ahead of the trap crop phenology, competition from kairomones emitted by the trap crop seems insufficient to explain the absence of a mass-trapping effect. Development of the attractiveness and retention of broad bean beetles by the semiochemical traps are therefore needed to increase their efficiency. Another aspect that further semiochemical trap development should address is that they can have a significant bycatch of beneficial insects, such as pollinators and natural enemies (Segers et al., 2023), but we did not observe substantial bycatch in our experiment and did not quantify it.

In conclusion, trap cropping could become a viable strategy to reduce damage by broad bean beetles in faba bean given some further refinement. As the strategy takes some time (extra sowing, work with semiochemical traps if combined with the trap crop) and resources (set aside land for trap crop and semiochemical traps), it will likely only be viable in high-value production of faba bean for human consumption. A possible but yet unexplored additional benefit from the extended flowering period provided by the two consecutively flowering cultivars is that it might attract more insect pollinators and so could increase crop pollination in the main faba bean crop (Bishop and Nakagawa, 2021), which might improve the cost-benefit-ratio of the trap crop strategy. More generally, successful control of broad bean beetle will likely require multiple methods that are combined to an integrated pest and pollinator management strategy (Egan et al., 2020; Lundin et al., 2021). The landscape ecology of this pest deserves attention, as it is conceivable that avoiding growing faba bean nearby faba bean fields in the previous cropping season could decrease the risk for severe damage, similarly to what has e.g., been found for pea moth (*Cydia nigricana*) in pea production (Schieler et al., 2024). In the case of faba bean for human consumption, there is also a need for research and development of post-harvest strategies that can remove damaged beans or insects in the harvested product, and thereby aid in meeting quality standards. Satisfactory control of the broad bean beetle will be needed in order to capitalize on the potential of faba bean to contribute to grain legume production for human consumption in Europe.

CRediT authorship contribution statement

Johansson Ylva: Writing – review & editing, Methodology, Investigation. **Lundin Ola:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Raderschall Chloé Aline:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109669.

Data availability

The data that support the findings of this study are openly available via the Swedish National Data Service upon publication: https://doi.org/10.5878/sqp5-zx59

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