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Can strip cropping reduce pest activity density and damage while increasing yield? A case study of organic cabbage and faba bean

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This study assessed how strip cropping white cabbage (*Brassica oleracea*) and faba bean (*Vicia faba*) affects the activity density of pests – diamondback moth (*Plutella xylostella*) and flea beetles (*Phyllotreta spp.*) – and how this affects crop yields. The setup consisted of three 270m^2 plots representing monocrops of faba bean and cabbage, and a plot of alternating strips of the two. The setup was established in 2018 and 2019. Activity density of *P. xylostella* was determined through yellow sticky trapping and *Phyllotreta spp.* activity density was determined by pitfall trapping. Crop yields were determined at harvest, and foliar damage to cabbage leaves was also assessed. The results showed that strip cropping reduced the activity density of *P. xylostella,* but no suppression effect was observed for *Phyllotreta spp.* Average foliar damage to cabbage was higher in the strip crop plot, but in 2018 the yield was also higher. Average faba bean yield was lower in the strip crop plot in both years. Our results indicate potential for cabbage-faba bean strip cropping to reduce the activity density of *P. xylostella* but not *Phyllotreta spp.* and to increase cabbage yield when overall pest pressure is moderate, but at the cost of faba bean yield. The case study shows that a *Brassica* vegetable – legume strip cropping system has potential for pest suppression in northern conditions, but agronomic compatibility of crop plants needs attention to ensure similar or higher productivity than a monocrop system.

Key words: biological pest management, organic farming, sustainable agriculture, vegetable production

Introduction

Since the introduction of modern agricultural techniques, fertilizers, and chemical pesticides, agriculture has favored monocrop systems, where many of the natural ecosystem services have been substituted with chemical inputs (Gagic et al. 2017). This has led to numerous examples of structural or functional deterioration of ecosystems (Geiger et al. 2010, Caro et al. 2016, Labrie et al. 2016). A growing global population, deterioration of ecosystems and climate change, simultaneously strengthen calls for sustainable intensification of agriculture and a concurrent reduction in the use of agrochemicals (Gagic et al. 2017). Therefore, novel cropping methods making better use of crop diversity should be developed and tested for their potential to improve productivity and suppress pests in different agroclimatic conditions, including the northernmost agricultural regions.

Strip cropping, syn. strip intercropping, is an agricultural practice whereby two or more crops are cultivated side by side in repeated strips. Whereas conventional monocrop agriculture is dependent on agrochemicals, strip cropping attempts to reduce or replace this dependency by providing a better environment for natural ecosystem services to flourish (Juventia et al. 2021). Several studies have reported benefits of strip cropping with increased productivity and higher land equivalent ratios (LER) compared to monocrops (Zhang 2019). However, strip cropping is a complex practice and its success depends on numerous factors including the correct crop combination, strip width, biotic and abiotic soil properties, crop management, soil type, landscape and weather conditions (Francis et al. 1986, Hauggaard-Nielsen et al. 2013, Labrie et al. 2016). As such, not all theoretical benefits of strip cropping can be realized in practice, and the cropping method can thus not be regarded to universally increase crop productivity (Bybee-Finley and Ryan 2018, Glowacka 2014a, Głowacka 2014b, Labrie et al. 2016, Xu et al. 2019). For example, Hauggaard-Nielsen et al. (2013) showed that a crop combination of annual maize and perennial grass-clover diminished maize yields due to the high competitive strength of grass-clover for nitrogen over maize.

Monocrop systems typically have a great reliance on agrochemicals for pest suppression and natural biological control is limited due to these chemicals affecting not only the pests but also non-target beneficial arthropods. In strip cropping systems, biological control could be improved by the increase of inter-crop diversity (Juventia et al. 2021). In a recent meta-analysis of cabbage, it was found that while yield of cabbage was reduced in intercropping by circa 7 %, pest injury was reduced by 48 % (Carrillo-Reche et al. 2023).

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Furthermore, strip cropping has the potential to increase crop productivity and biomass production per unit area - known as overyielding - mainly through improved resource partitioning and facilitation (Bybee-Finley and Ryan 2018). Resource partitioning offers more complete and efficient resource use, compared to traditional monocrop systems and can occur in spatial and temporal forms. However, resource partitioning is dependent on crops having different resource acquisition traits to minimize competition for resources, which could reduce the performance of a strip crop system compared to a monocrop system (see examples in: Bybee-Finley and Ryan 2018, Xu et al. 2019). Facilitation is when one crop species can provide another with a limiting resource that it needs to increase its yield or help it to better access growth resources. Legumes possess a well-studied ability to fix inorganic nitrogen into biologically usable forms due to symbiotic rhizobial bacteria, which are hosted in the root nodules of legumes (Kilian et al. 2001). The bacteria receive nutrients from the plant and in turn fix nitrogen. Thorsted et al. (2002) explored mechanisms of how legumes provide fixed nitrogen for their companion crops. They discovered that an important nitrogen source was from mineralization of decomposing above- and below-ground plant biomass and from rhizodeposition of turnover senesced roots. This biologically usable nitrogen would then be partly absorbed by the companion crop or left in the soil for the next crop rotation. How well legumes function in intercropping systems depends also on competition between the intercrops: for example, in a Danish study, biologically fixed N_2 by vetch was lower when intercropped with rye (circa 1.5 g N m^{-2}) compared to a monocrop of vetch (circa 8.6 g N m^{-2}) (Hauggaard-Nielsen et al. 2012). Furthermore, using legumes in strip cropping can have both spatial (improved resource use via biological nitrogen fixation) and temporal (less need for nitrogen fertilization in the year following a legume pre-crop) effects.

In this case study, we investigated a strip cropping system combining two annual crops, a pest-prone Brassica vegetable and a nitrogen-fixing legume, under organic farming conditions in south-eastern Finland in two consecutive years. Cultivated areas for white cabbage and faba bean in Finland are relatively small. For white cabbage, the area is 542 ha with 17 ha under organic farming protocols, and for faba bean 19 700 ha with 2857 ha under organic farming (Natural Resources Institute Finland statistics database 2018). The main crop with a high market value was white cabbage (*Brassica oleracea*), and the companion crop was a traditional pulse potentially used both as a seed and a green vegetable crop, faba bean (*Vicia faba*). Faba bean was selected due to its ability to produce extrafloral nectar which could provide support for beneficial natural enemies (Jones et al. 2017). It is also hypothesized to improve resource use efficiency through its ability to fix nitrogen via root symbionts, allowing reduced fertilization and beneficial soil-mediated follow-up effects for cabbage in the second year. The strip cropping system was compared to monocrops of both cabbage and faba bean. White cabbage and faba bean both have dominant pests that are associated with causing extensive damage. In northern borealis regions, such as Finland, diamondback moth (*Plutella xylostella*) (Lepidoptera: Plutellidae) and flea beetles (*Phyllotreta spp.*) (Coleoptera: Chrysomelidae) are among the most important pests of cruciferous crops (Augustin et al. 1986, Leskinen et al. 2011), while aphids (*Aphidoidea*) and pea weevils (*Sitona spp.*) are the main pests of faba bean (Stoddard et al. 2010, Wijerathna et al. 2021). Here, we focused on monitoring herbivore damage to cabbage and the main pests, *P. xylostella* and *Phyllotreta spp*.

Plutella xylostella is a major pest of cultivated cruciferous plants (Furlong et al. 2013). It oviposits into leaves and hatched larvae cause major foliar damage. On the other hand, *Phyllotreta spp.* are pests of many crops with the most common species detected on cabbage being *Phyllotreta undulata* and *Phyllotreta striolata*. Monitoring activity of both pests would enable us to assess an important factor in the efficiency of strip cropping as a pest control method.

This study aimed to measure the effectiveness of strip cropping as a method to limit crop damage by herbivores and improve crop yields through increased plant fitness and resource partitioning. We hypothesized that strip cropping would lead to (1) lower pest activity density, diamondback moth colonization and associated damage, (2) greater plant growth and higher crop yield, and increased parasitism rate and (3) higher LER than the monocrop. We also expected to find a positive edge effect in the strip-cropping plots due to the neighboring crops diversifying the complementary below- and above ground interactions between the crops. The study also aimed to provide actionable knowledge on using vegetables in strip-cropping systems at northern latitudes, which have been understudied.

Material and methods

Establishment of the field experiment

The experiment for the case study was conducted in a certified organic field in 2018 and 2019 at the Karila research station of the Natural Resources Institute Finland (Luke), Mikkeli (61°40’37.1”N 27°13’08.7”E).

The preparation and main field operations of the experimental field and pre-crop conditions are described in the Appendix (Appendix Table A1). We used white cabbage, *Brassica oleracea* var. *capitata*, cultivar Castello and faba bean, *Vicia faba*, cultivar Sampo. The three plots established in the experimental field were each sized 270 m^2 (10 × 27m), the distance between them was a minimum of 50 m at the closest point and the soil type was sandy moraine. More soil characteristics are shown in Appendix table A2. Plots were assigned to one of the following treatments: 1) cabbage monocrop (CB), 2) faba bean monocrop (FB) or 3) strip-crop of cabbage and faba bean in three-meter-wide strips (SC). In 2019, the plot positions were switched, so that where cabbage grew in 2018, faba bean was sown, and vice versa. The plots were divided into four sub-plots of 60 m^2 (6 × 10 m). Marginal rows between each subplot within the monocrop plots and strips in the strip crop plot was 55 cm. To stabilize the surroundings of each plot, 1.5 m of uncultivated soil was established to all sides of all the plots. To mitigate edge effects, a protective crop strip of 1.5 m was established at the ends of each plot. In monocrop plots, the protective strip comprised the same crop as the plot itself. In the strip crop plot, the protective strip featured the companion crop of the adjacent end strip; for instance, a cabbage strip was accompanied by a protective strip of faba bean, and vice versa (Fig. 1). The field area surrounding the experimental plots was under tillage and a late-season soil improving green manure mixture in 2018, and under spring wheat in 2019.

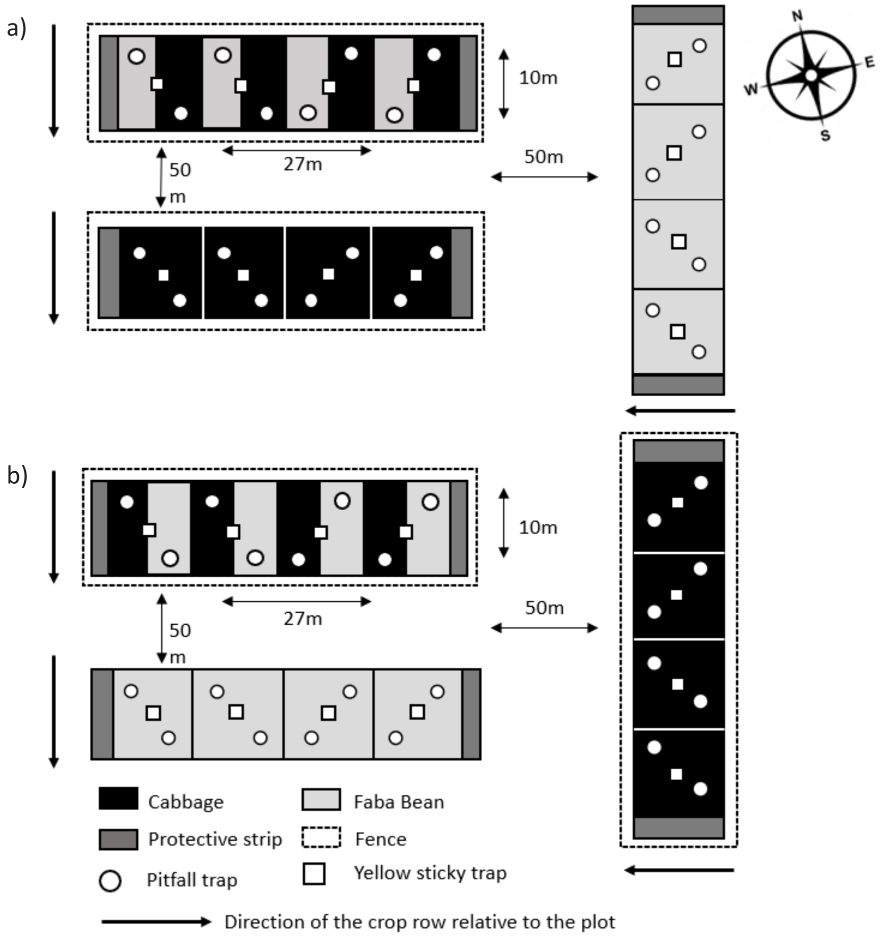

Fig. 1. Experimental field setup in 2018 (a) and 2019 (b). In monocrop plots the black indicates plot areas where cabbage plants were grown, and the light grey indicates where faba bean were grown. The pitfall traps are indicated by circles, yellow sticky traps by squares. Bold arrows next to the plots indicate the directions of the crop rows relative to the plot.

Weather conditions

Precipitation was recorded on site, and temperature data was collected from the Finnish meteorological institute's weather station located at Mikkeli airport (Finnish meteorological institute). In both years, precipitation was lower than the 30-year average from May to September. In 2018, the growing period was also considerably warmer than the 30-year average (Appendix Table A3).

Monitoring of the main cabbage pest insects adult diamondback moth (*Plutella xylostella* L.)

The relative activity density of adult *P. xylostella* was assessed using yellow sticky traps (size 20 × 20 cm, Biotus Oy, Finland). Trapping was done after the main field colonization, i.e., the main arrival of migrating *P. xylostella* to the field plot in each year, which was identified based on continuous visual observation. Following the first trapping event, a further two trapping intervals were conducted extending through July and covering the main activity period of adult *P. xylostella*. Yellow sticky traps have been used to control and monitor *P. xylostella* (Paudel et al. 2022). We used them, opposed to more commonly used pheromone traps, due to pheromone traps being based on attractive chemical odors, that could have had an potential influence on the strip cropping effect at the scale of the study conducted. We set up one yellow sticky trap in the middle of each CB and FB subplot and one in each cabbage strip of each SC subplot (Fig. 1). Traps were set for 48h on three occasions (Timepoint 1 (T1) = 28–30 June, T2 = 4–6 July and T3 = 18–20 July in 2018 and T1 = 25–27 June, T2 = 9–11 July and T3 = 23–25 July in 2019). After the trapping period, *P. xylostella* adults were counted. Monitoring adult *P. xylostella* populations has the advantage of predicting the upcoming larval pressure, and it can be a valuable early warning system for farmers, to help them plan insecticide application regimes (Baker et al. 1982, Walker et al. 2003), especially as this pest currently does not overwinter in Finland, but arrives as adults. Yellow sticky traps were attached to wooden sticks and the height was adjusted to set them slightly above the canopy level of faba bean. Traps in the cabbage monocrop and cabbage strips did not need height adjustments, due to cabbage not growing particularly tall.

Flea beetles (*Phyllotreta* spp.)

Adult *Phyllotreta* spp. activity density was monitored using pitfall traps. The trapping system is described in detail in the Appendix. Pitfall traps used to sample *Phyllotreta spp*. activity density were situated in an identical pattern between the monocrop plots and the strip crop plot (Fig. 1), which allowed us to determine activity density not only for the SC treatment, but the individual crop strips of the plot. Traps were set for one-week, with two-week breaks between each trapping period. Three trappings were conducted in 2018 (T1 = 12–19 June, T2 = 3–10 July and T3 = 24–31 July), and three were conducted in 2019 (T1 = 25 June–2 July, T2 = 16–23 July and T3 = 6–13 August). Traps were capped after each trapping period and transported to the laboratory where *Phyllotreta* spp. were identified to genus level.

Parasitism rate of diamondback moth (*Plutella xylostella*) larvae

The incidence of hymenopteran parasitoids, measured as a parasitism rate of *P. xylostella* larvae, was assessed in cabbage monocrop and strip crop plots by introducing lab-reared *P. xylostella* larvae into the plots for parasitoid exposure (as in Pinto et al. 2008). The larvae were reared on broccoli (*Brassica oleracea* var. *italica*) plants in a laboratory at the University of Eastern Finland. The population originated from the Netherlands and had been laboratory reared for several generations.

The number of *P. xylostella* larvae exposed in the field and the number of experimental replicates differed between 2018 and 2019 for practical reasons. In 2018, 16 broccoli plants were each infested with ten second-instar *P. xylostella* larvae in the laboratory and enclosed in micro-perforated polyethylene plastic bags 28 × 50 cm (with 9.3 holes/cm^2) (ClearBags, El Dorado Hills, USA) for transportation to the field. In 2018, two broccoli plants were placed in each of the four sub-plots of monocrop cabbage and in each of the four cabbage strips of the strip crop plot. The exposure was repeated three times from 6 August to 9 August. In 2019, one infested broccoli plant was placed in each of the four monocrop cabbage sub-plots and in each of the four cabbage strips of the strip crop plot. The exposure was repeated three times 6 August–9 August.

In both years, the broccoli plants were kept in the field for a 24 hour exposure, after which they were transported to the laboratory in micro-perforated bags. All plants were checked for any additional herbivores and predators, which were removed during collection. Plants were then placed in an Aralab FitoClima 1200PLH growth chamber (Rio de Mouro, Portugal) with a 16L:8D photoperiod and conditions of temperature 24 °C, and relative humidity 65% during the day and temperature 17 °C and relative humidity 85% during the night. The daytime light intensity was circa 400 µmoles m^{-2}s^{-1}. Emerging *P. xylostella* and parasitoid adults were counted every other day and the counting was continued for three weeks to ensure all pupae had emerged. The parasitism rate was determined as number of emerged parasitic wasps divided by the sum of emerged *P. xylostella* and parasitic wasps.

Crop yield and damage assessment

The crop yield and edge effect for cabbage were determined by sampling 16 individual cabbages per sub-plot in 2018 and 20 cabbages per sub-plot in 2019. This corresponded to four or five plants per row randomly selected from two rows in the strip or plot center and two rows at the strip or plot edge. Faba bean yield was determined from mechanically harvested seed, which was dried after harvest and sorted. Seed yield per hectare was determined for each subplot and adjusted to a 15% moisture level. For faba bean, the 1000 seed weight was calculated for three batches of 100 seeds from each subplot. The average of the subsamples multiplied by 10 was used to determine the 1000 seed weight at 15% moisture. Faba bean height and pod yield were analyzed by sampling randomly selected individual plants from both monocrop and strip crop treatments. In 2018, 80 plants were sampled from both monocrop and strip crop treatments. In 2019, 75 plants were sampled from both monocrop and strip crop treatments. The edge effect for faba bean was determined from the same randomly collected individual plants (five per row). In 2018, 40 of these plants were from the edges of the plots and 40 from the center. In 2019, 35 of these plants were from the edges of the plots and 40 from the center.

Individual cabbage heads were trimmed (with all external leaves not tightly bound to the head removed) before conducting the fresh weight measurement. No further trimming to separate marketable or non-marketable heads was done. The outer leaves of each cabbage were cut and photographed against a white background for leaf damage estimation. Foliar damage caused by herbivores was assessed visually from pictures of 17–20 leaves per cabbage head, corresponding to approximately 3000 individual leaves. A damage value on a 1–5 scale (Table 1) was given to each leaf using a methodology described by Katz and Ibáñez (2016). Damage values for all cabbages per treatment were averaged. Cabbage damage at the plot edge and center were compared to assess potential edge effects. All leaves were analyzed by the first author to minimize observation bias. In addition, the size of cabbage heads was assessed by measuring their width (cm) after trimming and cutting in half.

Table 1. Foliar damage analysis levels and corresponding scale of the damage as a percentage of the leaf area removed. Damage scaling model by Katz and Ibáñez 2016.

Damage scale	Corresponding damage percentage
1	<1
2	1-5
3	6-15
4	16-50
5	>50

Land equivalent ratio

The yield benefit of strip cropping was assessed by calculating land equivalent ratio (LER) indices to compare the yields produced by each treatment in a given area. The yields of the strip cropped plants per unit area were divided by the monocrop yield in the same area. This calculation gave a coefficient indicating how much area a monocrop requires to achieve the same yield. These coefficients for each plant species were then summed to calculate the LER index.

$$LER = \sum_{i=1} \frac{Ys}{Ym}$$

Where Ys is the yield per unit area in the strip crop, and Ym is the yield per unit area in the monocrop. Cabbage yield per unit area (kg ha^{-1}) was estimated by multiplying the average weight of a cabbage head in a treatment by the number of cabbage heads in a hectare for monocrop value and by half hectare for strip crop value. Faba bean yield per unit area (kg ha^{-1}) was weighted directly from the harvested yield.

Statistical analyses

Foliar damage and the yield of cabbage and faba bean were not analyzed statistically, but descriptively, due to all having a sample size of one. The number of adult *P. xylostella* and *Phyllotreta* spp., and the parasitism rate (%) of *P. xylostella* were analyzed using generalized linear mixed models (GLMM). The latter was analyzed using the assumption of beta distribution (with a logit link). A few boundary values of 0 and 1 were changed to 0.001 and 0.999

respectively, to keep them in the analysis. An ideal way would have been to use the assumption of Poisson or a more flexible negative binomial distribution for the number of adult *P. xylostella* and *Phyllotreta spp*. However, we ran into estimation and convergence problems with these models, and thus we were forced to simplify our models. Due to the skewness of the pest distributions, the values of the response variables were log-transformed (ln [x+1]) for the analysis, but the results were transformed back to the original scale (e^x-1). For both pests, years 2018 and 2019 were analyzed jointly. Treatment (cabbage (CB), faba bean (FB), and strip crop (SC), year (2018 and 2019) and timepoint (T1, T2 and T3), and all their interactions were used as fixed effects. In the case of *Phyllotreta spp.* the treatment strip crop was further divided into individual crop strips C (cabbage) and F (faba bean). Observations within a plot were averaged to avoid pseudoreplication, leading to sample sizes of 36 and 60 for *P. xylostella* and *Phyllotreta* spp, respectively. The parasitism rate of *P. xylostella* was not measured on FB, and thus the number of real replicates was 30. Treatments within the strip crop (C and F) were blocked by pairs in the latter model and were considered in the model through a random effect of the block. The dependency of timepoints on measurements from the same plot was modelled through compound symmetry covariance structure. The Tukey-Kramer test, which assumes equal variances but not equal sample size for treatments, was used for pairwise comparisons with a significance level of α=0.05. This allowed us to compare monocrops in cases where the emphasized avoidance of pseudoreplication reduced the sample size to one at a single timepoint. Due to the unbalanced sample sizes of the treatments, the used method was found to be the most effective, but we have been cautious in interpreting the results. The parasitism rate was fitted by using the residual pseudo-likelihood estimation method (RSPL). Both models were fitted by using the restricted maximum likelihood estimation method (REML) and degrees of freedom were calculated using the Kenward-Roger method (Kenward and Roger 2009). The analyses were performed using the GLIMMIX procedure of the SAS Enterprise Guide 7.15 (SAS Institute Inc., Cary, NC, USA).

Results

Main cabbage pests

Activity density of adult *Plutella xylostella*

Plutella xylostella activity density varied greatly between years, with 998 adults collected in 2018 and 3574 in 2019, a difference of 258%. CB had a higher number of *P. xylostella* compared to FB (t_6=3.13, *p*= 0.046) and SC (t_6=4.54, *p*= 0.001) but the difference between FB and SC was not significant (t_6=0.58, *p*= 0.838) (Fig. 2). The *P. xylostella* population diminished over the season, with each timepoint having significantly fewer observations than the previous one: from timepoint 1 to 2 (t_{12}=3.03, *p*= 0.026) and from timepoint 2 to 3 (t_{12}=11.22, *p*< 0.001). The activity density of *P. xylostella* was also analyzed between treatments at each timepoint in both years, which allowed us to better assess fluctuations in the *P. xylostella* population. In 2018, at T1, CB had a higher number of *P. xylostella* compared to SC ($t_{17.98}$=3.39, *p*= 0.009), at T2 no significant differences were observed, and at T3 CB had a higher number of *P. xylostella* compared to SC ($t_{17.98}$=2.72, *p*= 0.036) (Fig. 3). In 2019 at T1 or T2 no significant differences were found, but at T3, CB had a higher number of *P. xylostella* compared to FB ($t_{17.98}$=3.11, *p*= 0.016) and SC ($t_{17.98}$=5.18, *p*< 0.001) (Fig. 3).

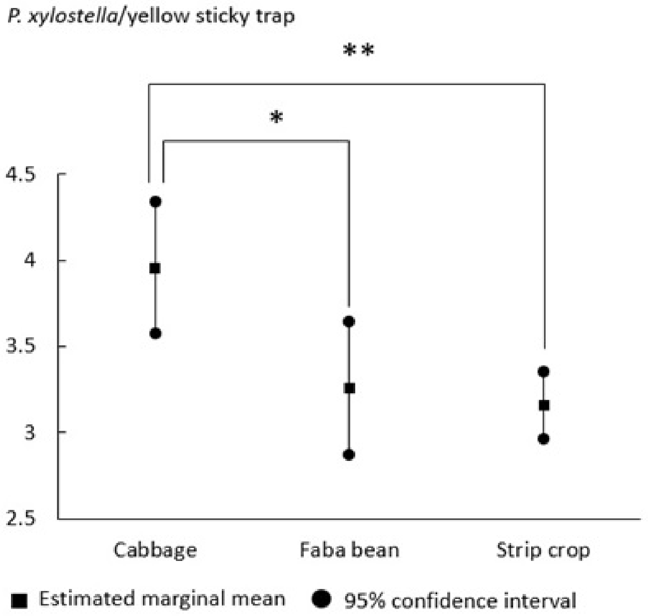

Fig. 2. Estimated marginal means of *P. xylostella* adults caught on yellow sticky traps during 2018 and 2019 for each crop type (mean ± 95% confidence limits). A marginal mean is the mean response for each category of a factor, adjusted for any other variables in the model. The model is based on 36 real replicates.

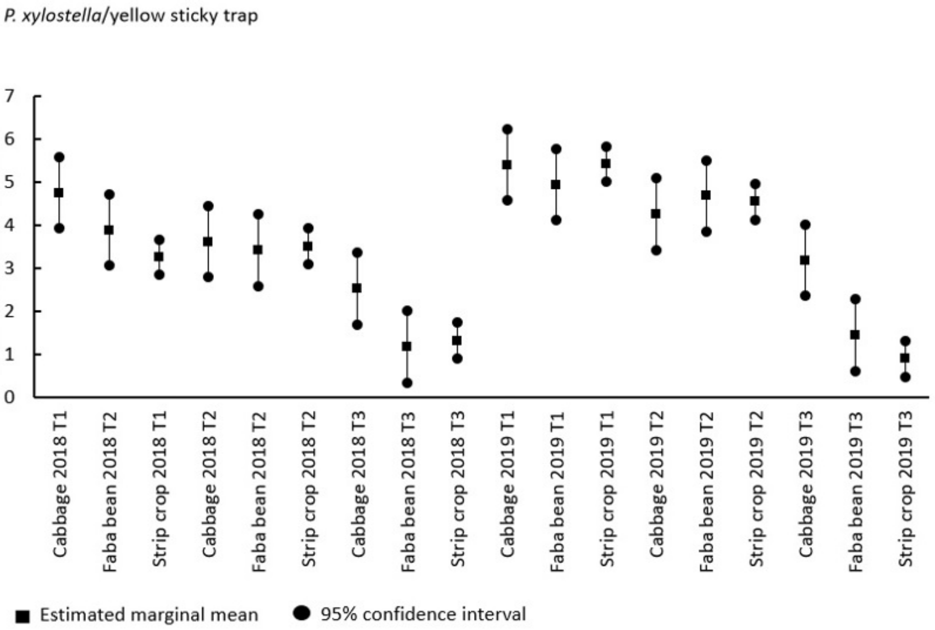

Fig. 3. Estimated marginal means of *P. xylostella* adults caught on yellow sticky traps at each timepoint (T) in 2018 and 2019 for each crop type (mean ± 95% confidence limits, n=36). A marginal mean is the mean response for each category of a factor, adjusted for any other variables in the model. Timepoints for 2018 : T1 = 28–30June, T2 = 4–6 July, T3 = 18–20 July. Timepoints for 2019 : T1 = 25–27 June, T2 = 9–11 July, T3 = 23–25 July. The model is based on 36 real replicates.

Activity density of adult *Phyllotreta* spp.

Phyllotreta spp. activity density also varied greatly between the years, with 189 adults collected in 2018 and 559 in 2019, a difference of 296%. Statistically significant differences between the treatments were not observed (Fig. 4), but there was a marginally significantly higher number of *Phyllotreta spp.* in CB compared to FB ($t_{9.003}$=2.67, *p*= 0.099). The *Phyllotreta spp.* population also diminished over the season, but the population fell sharply between the first and second timepoint ($t_{23.46}$=6.39, *p*< 0.001) and the lowest level in population was recorded during the 2nd timepoint. The activity density of *Phyllotreta spp.* was also analyzed between treatments at each timepoint in both years, which allowed us to better assess the fluctuation of the *Phyllotreta spp.* population. However, we did not observe any significant differences (Fig. 5).

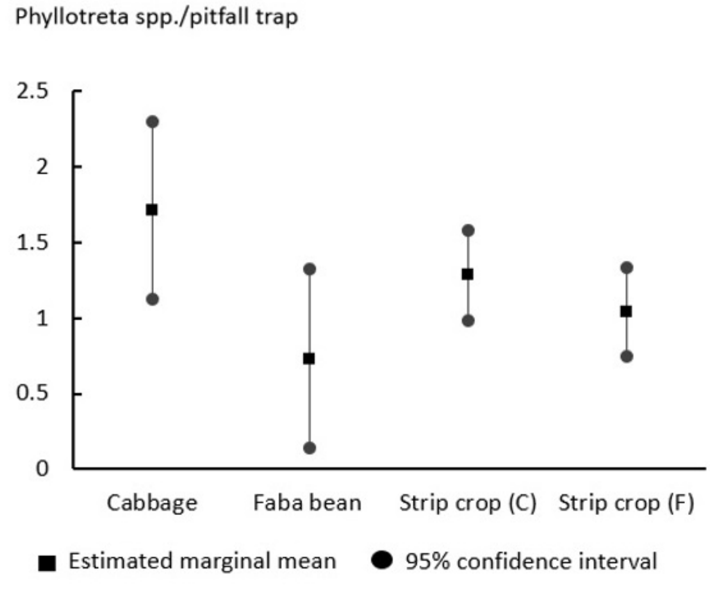

Fig. 4. Estimated marginal means of *Phyllotreta spp*. adults caught in pitfall traps during 2018 and 2019 for each crop type (mean ± 95% confidence limits). A marginal mean is the mean response for each category of a factor, adjusted for any other variables in the model. The model is based on 60 real replicates.

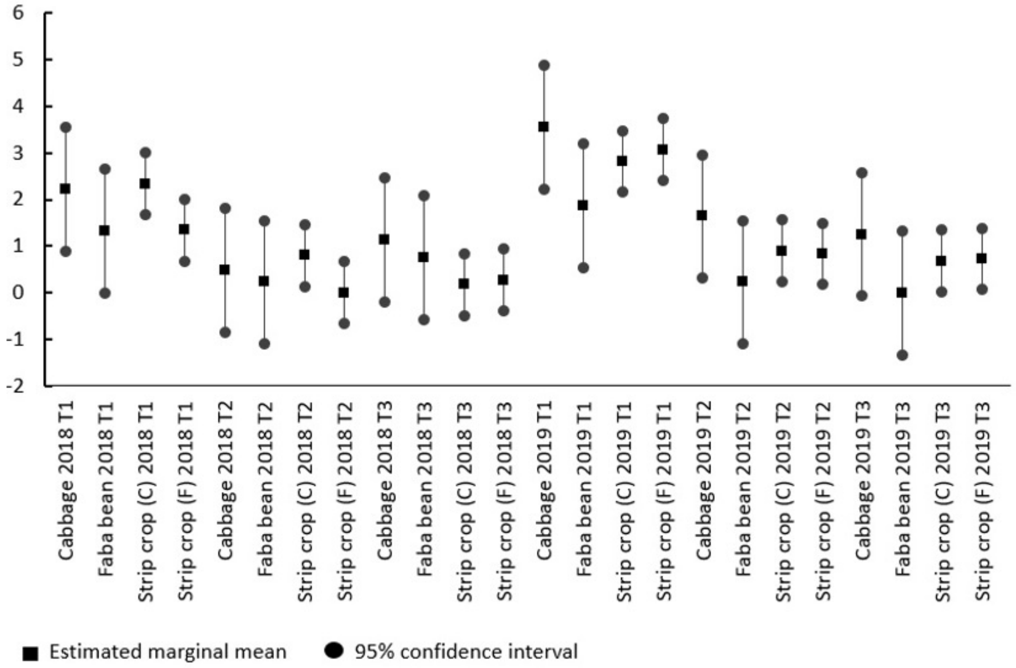

Fig. 5. Estimated marginal means of *Phyllotreta spp*. adults caught in pitfall traps at each timepoint (T) in 2018 and 2019 for each crop type (mean ± 95% confidence limits). A marginal mean is the mean response for each category of a factor, adjusted for any other variables in the model. Timepoints for 2018 : T1 = 12–19 June, T2 = 3–10 July, T3 = 27–31 July. Timepoints for 2019 : T1 = 25 June–2 July, T2 = 1 June–23 July, T3 = 6–13 August. The model is based on 60 real replicates.

Parasitism rate of *Plutella xylostella* larvae

The parasitism rate of *P. xylostella* larvae was not significantly different between CB and SC plots during any of the timepoints in 2018, or in 2019. However, in 2019, parasitism rate was significantly lower in SC in T1, compared to T2 ($t_{12.23}$=-3.04, *p*= 0.026) and marginally higher in T2, compared to T3 ($t_{13.26}$=2.33, *p*= 0.087) (Fig. 6). In 2018, the parasitism rate was 58% on the CB and 52% on the SC over all three timepoints. In 2019, those estimates were 62% on the CB plot and 50% on the SC plot, respectively.

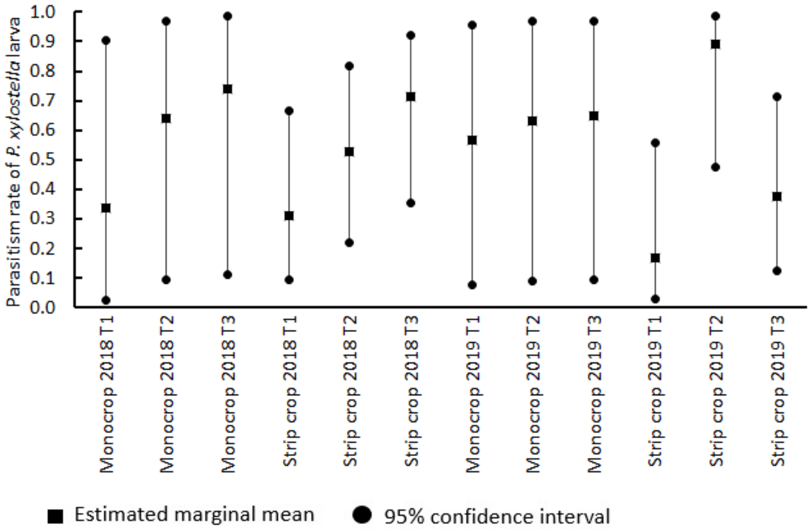

Fig. 6. Estimated marginal means of *P. xylostella* larval parasitism rate (%) at each timepoint (T) in 2018 and 2019 for monocrop cabbage and strip crop cabbage (mean ± 95% confidence limits). A marginal mean is the mean response for each category of a factor, adjusted for any other variables in the model. Timepoints for 2018: T1 = 6–7 August, T2 = 7–8 August, T3 = 8–9 August. Timepoints for 2019: T1 = 6–7 August, T2 = 7–8 August, T3 = 8–9 August. The model is based on 30 real replicates.

Cabbage yield and foliar damage

In 2018, the average fresh head yield and average head width were higher in SC (2071 g and 16.20 cm respectively) than CB (1624 g and 14.48 cm respectively) (Fig. 7). Furthermore, in CB, cabbages in the middle of the plot had a higher average fresh head yield (1657 g) than at the edge (1591 g). In SC, cabbages at the middle of the plot had a higher average fresh head yield (2131 g) than at the edge (2011 g). In 2019, average fresh head yield and average head width were marginally higher in CB (2333 g and 16.84 cm respectively) than in SC (2277 g and 16.46 cm respectively) (Fig. 7). Furthermore, in CB, cabbages in the middle of the plot had a higher average fresh head yield (2463 g) than at the edge (2138 g). In SC, cabbages at the middle of the plot had a higher average fresh head yield (2588 g) than at the edge (1812 g).

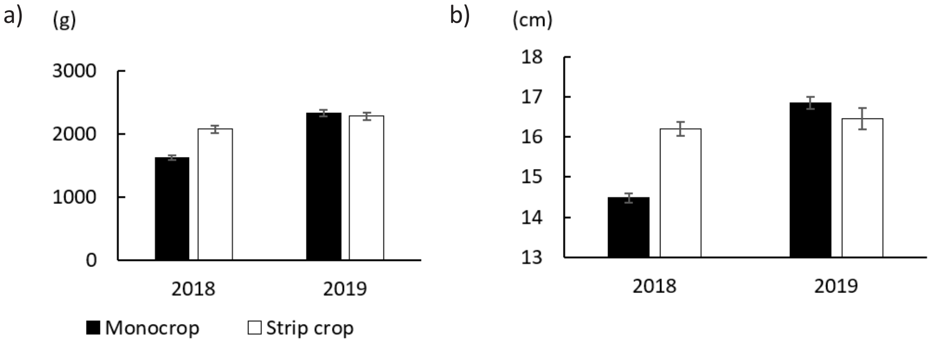

Fig. 7. cabbage head fresh yield (a) and head width (b) in the monocrop, and strip crop plots in 2018 and in 2019 (mean ± SE).

Cabbages in the SC plot were more herbivore damaged than in the CB plot in both years. In 2018, CB had a damage value of 1.96 compared to 2.01 in SC (Table 2). In 2019, CB had a damage value of 1.65 compared to 1.82 in SC (Table 2).

Table 2. Mean foliar damage levels in Cabbage monocrop and Strip crop treatments. The damage scale is between 1 to 5.

Year	Cropping system	Damage scale	Standard deviation
2018	Monocrop	1.96	0.34
	Strip crop	2.01	0.38
2019	Monocrop	1.65	0.21
	Strip crop	1.82	0.25

In 2018, cabbage leaves in the CB plot had a damage value of 1.92 at the edge of the plot and 2.00 at the center of the plot. In the SC plot, in 2018, cabbages had a damage value of 2.03 at the edge of the plot and 1.99 at the center of the plot. In 2019, cabbage leaves in the CB plot had a damage value of 1.64 at the edge of the plot and 1.66 at the center of the plot. In the SC plot, in 2019, cabbages had a damage value of 1.84 at the edge of the plot and 1.80 at the center of the plot.

Faba bean dry seed yield

In 2018, the average faba bean seed yield and weight of 1000 seeds were higher in FB (3189 g and 315 g respectively) than SC (1937 g and 290 g respectively) (Fig. 8a and b, respectively). In 2019, the average faba bean seed yield was higher in FB (1673 g) than SC (1260 g), but weight of 1000 seeds was higher in SC (274 g) than FB (263 g) (Fig. 8a and b, respectively).

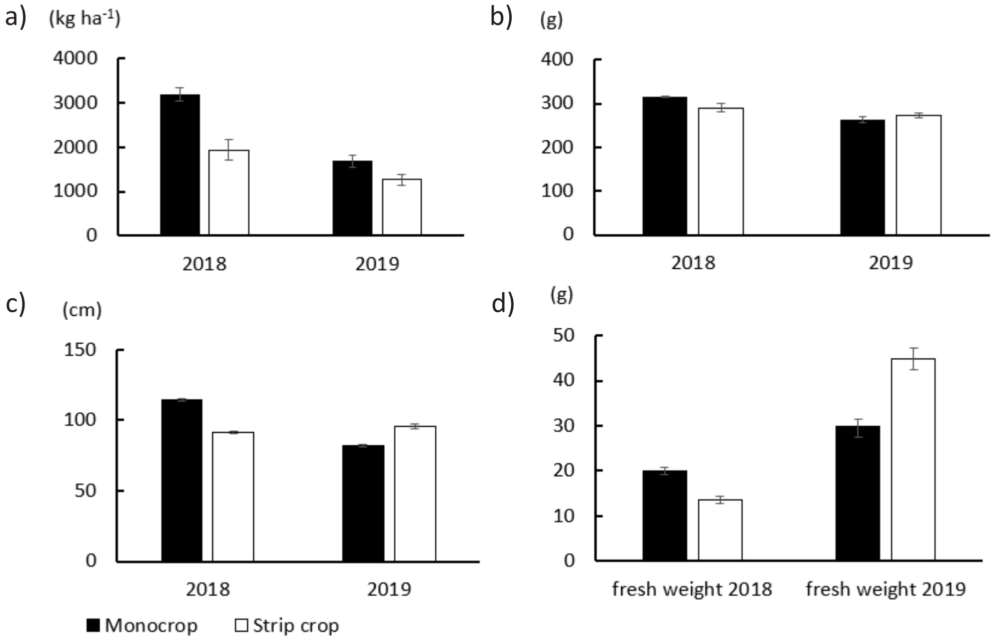

Fig. 8. Average faba bean seed yield (a) and weight of 1000 seeds (b), height (c) and fresh pod weight (d) in the monocrop and strip crop plots in 2018 and in 2019 (mean ± SE).

Yield components

In 2018, the faba bean plant height and the fresh pod weight were higher in FB (115 cm and 20 g, respectively) than in SC (92 cm and 14 g, respectively) (Fig. 8c and d, respectively). In FB, faba beans in the middle of the plot had a higher average height (116 cm) than at the edge (113 cm), but the average fresh pod weight was higher at the edge of the plot (22 g) than in the middle (18 g). In SC, faba beans in the middle of the plot had a higher average height (95 cm) than at the edge (88 cm), but the average fresh pod weight was higher at the edge of the plot (16 g) than in the middle (11 g).

In 2019, the faba bean height and fresh pod weight were higher in SC (96 cm and 45 g, respectively) than in FB (82 cm and 30 g, respectively) (Fig. 8c and d, respectively). In FB, faba beans in the middle of the plot had a higher average height (84 cm) than at the edge (82 cm), but the average fresh pod weight was higher at the edge (24 g) than in the middle (21 g). In SC, faba beans in the middle of the plot had a higher average height and fresh pod weight (105 cm and 40 g, respectively) than at the edge (88 cm and 36 g, respectively).

Land equivalent ratio

The strip crop treatment had an LER value of 0.94 in 2018 and 0.87 in 2019. Both values were lower than 1, indicating that strip cropping produced a lower yield in the same land area as the monocrops.

Discussion

In this study the effects of strip-cropping on pest activity density and crop damage of cabbage, and yield were shown to vary with pest species, treatment, and year. Importantly, strip-cropping appeared to have overall beneficial effects on suppression of *P. xylostella* and yield of cabbage, neutral effects on *Phyllotreta spp,* but negative effects on yield of faba bean.

We observed that strip cropping reduced the activity density of *P. xylostella*, but not the activity density of *Phyllotreta spp.* In the case of *P. xylostella*, the effect was evident both as a seasonal average and during the first and last timepoints. However, the parasitism rate of *P. xylostella* larvae was not affected by strip cropping, indicating that the decreased activity density was not attributable to greater parasitoid activity but rather to other consequences of strip cropping. While strip cropping did not increase parasitism rate of *P. xylostella*, it also did not reduce it. This is likely due to specialized parasitoids being highly capable of locating their prey even in diversified surroundings. However, the observed fluctuations in parasitism rates throughout the 2019 season in the strip cropping plot, a phenomenon absent in the monocrop cabbage, suggest that strip cropping may introduce greater variability to parasitism rates. We also found that the adult *P. xylostella* population was at its highest at the start of the season (in June), mirroring the migrating behavior of the pest and consequently the importance of disturbing the host finding phase of this pest through diversified cropping systems. But regardless of that, the strip crop had a lower activity density than the monocrop, indicating monocropping with a more concentrated resource base to be more attractive to the adult *P. xylostella*. Intercropping cabbage with a wide range of companion crops, such as tomato (*Solanum lycopersicum*), dill (*Anethum graveolens L.*), safflower (*Carthamus tinctorius L.*), garlic (*Allium sativum L.*), oat (*Avena sativa L.*), barley (*Hordeum vulgare L.*) (Paudel et al. 2022) and faba bean (Qasim Mohammed and Adnan Alyousuf 2021) has been used to successfully control *P. xylostella*. The results of this study confirm these findings. It also demonstrates that strip cropping cabbage with faba bean is a viable method in controlling *P. xylostella* at northern latitudes. However, it is also important to note that *P. xylostella* cannot overwinter at northern latitudes, such as Finland, and the pest migrates over long distances carried by the wind. This causes large variation in yearly pest pressure exerted by this pest and strip cropping may exhibit variable pest control performance under different levels of pest pressure.

Strip cropping was less efficient at limiting adult *Phyllotreta spp.* numbers but performed similarly to the monocrop. This highlights a need for tailoring several IPM strategies together to combat specific pests, as one strategy might not work to suppress all pest insects with differing host finding capabilities, preferences and responsiveness to diversified cropping. However, the *Phyllotreta spp.* population was also highest at the start of the season, indicating that it might be strategic to develop repelling strategies targeting them during this time. Prevailing weather conditions also play a role in *Phyllotreta spp.* emergence early in the growing season and can affect the activity density of the pest. In our study, the beginning of the growing season differed in terms of temperature and precipitation between the two years. May 2018 was warmer and drier than the 30-year average, while May 2019 was within the average temperature over the 30-year average but received more rain (see details in Appendix Table A3). In a study by Parker (2012), the author found companion cropping to be inefficient at controlling *Phyllotreta spp.*, but trap cropping was effective. We could hypothesize that to control *Phyllotreta spp.* more efficiently a trap cropping method could complement strip cropping.

While we observed significantly fewer *P. xylostella* in SC compared to CB, and no significant difference in *Phyllotreta spp.* observations, this did not correlate with lower foliar damage in SC. This could be due to SC having half of the cabbage area compared to CB and herbivorous insects being more concentrated on the crop available in SC. Alternatively, other non-studied herbivorous pests could have contributed to the total foliar damage. Our study may also indicate that other factors, e.g., biological control, might vary between treatments and influence the overall damage in SC and CB. As such, no direct relationship between the observed foliar damage and the trapped pest insects can be drawn and further research is needed to untangle the potential factors interplaying. Foliar damage between the edge and the center of monocrop cabbage and strip crop plots was similar, indicating that the edge of the plot did not function as a barrier preventing pests from reaching the center.

Our case study mimicked field conditions due to the size of our field site and subplots, but consequently had low replicate numbers. Replicating the treatments multiple times in the area available, in a Latin square design for example, would have been possible; but only with a substantially smaller plot size, which may have enabled insect dispersion to hide differences between neighboring treatments. Replicating the set-up in several fields would have been statistically sound, but would not have been practically achievable. Therefore, this case study is a demonstration of a practically and ecologically sound strip cropping system combined with crop rotation, which can provide farmers with practically valuable information as a diversification strategy, but at the cost of some statistical robustness.

Landscape composition and environmental conditions have direct effects on both pest and natural enemy abundances and activity densities (Karp et al. 2018), which might partially explain the lack of consensus in literature on the overall effect of strip-cropping, even for studies with similar within-field crop composition. Potting et al. (2005) reviewed that 52% of studies comparing pest insect populations in monocultures and polycultures reported greater populations in monocultures, while 48% of the studies reported either the opposite or no effect. The annual changes in pest pressure, and different pest responses to strip cropping observed in our study and in previous studies highlights the complexity of successfully implementing pest control using strip cropping (Labrie et al. 2016).

Further research on long-term experiments would be needed to replicate the studied strip-cropping combination in several fields with different landscape contexts and estimate the overall benefit of the strip-cropping and untangle interplaying factors. In our study, we aimed to limit additional external variation created by potential landscape factors by using the same field plot in both years.

Importantly, strip-cropping with faba bean increased the cabbage yield in 2018, but not in 2019. This is reflected in the foliar damage, where strip crop was consistently more damaged than monocrop, but the difference was greater in 2019 compared to 2018. Sanchez and Wade (1996) showed that during low *P. xylostella* pressure, a strip crop system of black bean and broccoli yielded 1.3 times more broccoli than in the monocrop. These results are similar to our results from 2018 when pest pressure was lower and cabbage yielded more in the strip crop system. However, faba bean yields, when strip cropped with cabbage, were either lower (2018) or similar (2019), compared to the monocrop. This would explain our LER index being lower than one, especially in 2019. Our results differ from those of Shanmugam et al. 2022 who obtained an LER value above 1 for a cabbage – faba bean intercrop. However, like ours, their study and a study by Lepse et al. (2017) showed increased cabbage yields when intercropped with faba bean compared to a monocrop, due to cabbage being more competitive for soil mineral nitrogen. In our study we used different cultivars to those used in the study by Shanmugam et al. (2022), our field design used crop strips instead of rows, and the geographical locations were different. These differences in experimental design might have led to cabbage outcompeting faba bean, reducing its yield and the LER value in the SC. *Brassica* – legume intercrops have been shown to result in LER values above 1, but the efficacy of strip cropping appears to be dependent on the companion crop species (Jeromela et al. 2017), cultivar (Song 2020) and the strip or row width, which have all been shown to affect the productivity of intercrop systems (Raza et al. 2020, van Oort et al. 2020).

Numerous studies with other crops have also shown positive effects of strip cropping through increased yields, improved biological pest control and reduced need for agrochemicals (Bybee-Finley and Ryan 2018, Hauggaard-Nielsen et al. 2013, Labrie et al. 2016). Ecological services provided by strip cropping, such as decreased soil degradation compared to monocropping (Zhang 2019) would also become more pronounced over time and could lead to yield increases. However, while strip cropping can increase yields, profitability of the crops for farmers also depends on the market prices and needs to be considered when assessing functionality of strip cropping. There are also well documented benefits of additional crop rotations over a longer period of time and under more average weather and pest conditions (D'Acunto et al. 2018, Zhang 2019). It is important to note that strip cropping is only one form of intercropping. In a meta-analysis by Carrillo-Reche et al. 2023, mixed intercropping with multiple crops species, and later sowing date for cabbage, was found to be beneficial for cabbage yield. In the cabbage – faba bean system, the lack of physical support for the faba beans at the edges causes them to bend and fall, which may have negatively impacted the yield in the SC. Had the companion crop of faba bean been similar in structure, maize for example, or if instead of strip cropping, mixed intercropping had been used, the physical support given at the edges for faba beans could have prevented them from bending and falling.

Conclusion

Our results offer insight into the functionality of a vegetable-legume strip cropping system cultivated at northern latitudes, and add to literature indicating that strip-cropping is a complex practice that may be effective and offer positive ecological services, but not under all conditions. In our study, although strip cropping did lower the activity density of *P. xylostella*, it did not repel *Phyllotreta spp.*, or increase *P. xylostella* parasitoid activity, highlighting the need to tailor crop systems for specific pests and to combine strategies together. The LER below 1 observed in both years highlights the complexity of successful use of the method with this particular crop combination. Strip cropping has been shown to be dependent on compatibility of the crops and their susceptibility to abiotic and biotic factors. Crop compatibility issues, the warm summer of 2018, and the high activity density of *P. xylostella* and *Phyllotreta spp.* in 2019, may have influenced the overall crop yield observed in this study, compared to the majority of earlier studies. These findings support the hypothesis that for strip cropping to be effective, an appropriate crop and cultivar combination must be selected. In addition, the intercropping set-up needs consideration and its agronomical and biological effect may vary with yearly variation in pests and weather.

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Appendix

Establishment and management of the field experiment

The experimental field was under certified organic production and the whole field plot was 3.56 hectares in area. The pre-crop was a timothy-red clover mixture that was incorporated into the soil in August 2017 using a Kvick-Finn soil cultivator (BT-Agro Oy Ab, Helsingby, Finland) to control weeds.

Prior to the experiment, the soil was cultivated in spring 2018 using a Kvick-Finn soil cultivator and harrowed to remove weeds. Plots were prepared for planting with a rotary tiller. For fertilization, organic bone meal–based commercial fertilizer (Ecolan Agra 8-4-8, Tampere, Finland) was used at quantities of 2 000 kg ha^{-1} (160 kg N ha^{-1}) for cabbage and at 500 kg ha^{-1} (40 kg N ha^{-1}) for faba bean, which was added manually to the plots (on 16 May 2018 and 16 May 2019) followed by mechanical harrowing. Soil analysis was performed on all three plots to determine the properties and any differences that may exist between the plots. The soil type of all three plots was sandy moraine and soil properties including pH, soil organic carbon (SOM), cation exchange capacity and nutrients were all similar between the three plots (Table A2). Sprinkler irrigation was used according to cabbage requirements, which is when precipitation over the previous 14 days was lower than 10 mm. This occurred on one occasion in 2018: 1st June and on one occasion in 2019: 28th June. The cabbage (*Brassica oleracea* var. *capitata* cultivar Castello) seedlings used were produced by a local farmer. The distance between seedlings and rows was 60 cm. The faba bean (*Vicia faba* cultivar 'Sampo') was purchased as organic seed (estimated germination rate 97%; 1000-seed weight 302g in 2018, 268g in 2019, Naturcom Oy, Ruukki, Finland) and sown with a target seeding rate of 70 seeds/m^2, at 6cm depth. The strip crop plot had eight alternating strips, four of cabbage and four of faba bean (Fig.1). The same crop-specific plot preparation was used for the monocrop and the strip crop plots in both years. After harvest in autumn 2018, the remaining crop residue was crushed with a fallow crop crusher and the soil was harrowed twice with a rotary harrow. In 2019, the plots were harrowed using a drag harrow prior to establishment.

Pitfall trapping

Pitfall traps were assembled as two-cup systems, where an outer transparent plastic cup (8.5cm diameter and 8cm depth) (Lahtisen vahavalimo, Oitti, Finland) was dug into the soil to ensure that the edge was just below the soil level and remained there for the duration of the experiment. A second identical cup was positioned inside the outer cup to serve as the trap. After each week of trapping, the trap cup was removed and closed with a lid. The base cup was covered with a lid during the two-week periods between trappings. Above each trap there was a 13 × 13 cm dark brown plywood rain guard, which served to keep small vertebrates out. Note that rain guards being non-transparent could possibly affect the yield (Bell et. al. 2014). For sampling, 100ml of trapping liquid comprising 20% propylene glycol ($C_3H_8O_2$, 1-2-propyleneglycol, Tyfocor L) with a dash of standard dishwashing liquid (Rainbow, Finland) to lower the surface tension was used.

Table A1. Details and times of field operations for the experiment

Practice	Year	Date(s)	Comments
Cabbage planting	2018	17.–18.5.	Same day for monocrop- and strip crop plots
	2019	28.5.	
Faba bean sowing	2018	22.5.	
	2019	5.6.	
Protective fleece in place	2018	17.–31.5.	
	2019	28.5–11.6.	
Weeding	2018	31.5, 11.6. and 25.6.	Weeding was done only when needed
	2019	10.6, 14.–15.6. and 10.–12.7.	
Sprinkler irrigation	2018	1.6.	Irrigation was done only when needed
	2019	28.6.	
Cabbage harvest	2018	21.–23.8.	
	2019	26.–28.8.	
Faba bean harvest	2018	4.9.	
	2019	26.9.	

Table A2. Results of the soil analysis of the experimental plots

Analysis	Unit	Cabbage monocrop plot	Faba bean monocrop plot	Strip crop plot
Soil type		Sandy moraine	Sandy moraine	Sandy moraine
Soil organic carbon	%	3.0 – 5.9	3.0 – 5.9	3.0 – 5.9
pH		6.7	6.4	6.4
Calcium	mg l^{-1}	1800	1500	1300
Phosphorous	mg l^{-1}	13	11	9.3
Kalium	mg l^{-1}	160	150	140
Magnesium	mg l^{-1}	200	180	160
Sulfur	mg l^{-1}	7.3	7.6	8.3
Cation exchange capacity	cmol kg^{-1}	12	11	10

Table A3. Average precipitation and temperature data from 2018 and 2019 in Mikkeli

Year	Month	Monthly precipitation (mm)	Average monthly precipitation (mm) 1981–2010	Monthly average temperature	Monthly average temperature (°C) 1981–2010
2018	May	13.5	40	13.7	9.6
2019	May	67.8		9.4	
2018	June	24.6	67	14.5	14.1
2019	June	20.7		16.5	
2018	July	54.2	76	19.5	16.9
2019	July	42.5		15.3	
2018	August	56.0	77	17.0	14.6
2019	August	41.9		14.6	
2018	September	76.1	54	11.3	9.4
2019	September	54.9		9.4	