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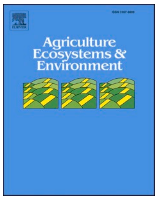

Cauliflower strip cropping promotes ground-dwelling arthropod richness and spider abundance

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ABSTRACT

While large-scale agriculture is an important driver of biodiversity loss, diversified agricultural cropping systems may have potential to support farmland biodiversity. Strip cropping is a form of crop diversification in which crop strips are alternated in the same field and thereby increasing in-field crop heterogeneity and edge-density while using existing farm machinery. Although strip cropping may provide more diversity in habitat, food, and shelter at small spatial scales, it is still unknown how arthropod communities respond to a variety of strip widths of intensively managed vegetable crops, and whether strip cropping can provide nearby refuge sites for arthropods during and after harvest. We studied responses of the ground-dwelling arthropod community to strip widths of 6, 12, 24 and 48 m, both pre- and post-harvest. The study was conducted in cauliflower strips in a large-scale, commercial organic strip cropping field in 2018 and 2019. The cauliflower strips were bordered by annual flower strips on one side and by grass-clover (year 1) or potato (year 2) on the other side. Increasing strip width was associated with lower spider activity density and lower richness of the ground-dwelling arthropod community, and higher rove beetle activity density. Ground beetles showed variable responses to strip width depending on genus and year. Ground beetles of the genus *Harpalus* showed negative responses to increasing strip width in both years and genera *Bembidion* and *Pterostichus* showed positive responses to increasing strip width in 2019. Crop harvest had a negative influence on ground-dwelling arthropod activity density and community richness, and this effect was more pronounced in narrow strips than in wider strips. Our results indicate that strip cropping cauliflower can support ground-dwelling arthropod community richness and activity density of certain species groups in large-scale agricultural fields, but does not enhance short-term post-harvest recolonization.

1. Introduction

Biodiversity is declining at a global scale (IPBES, 2019) and agricultural intensification has been identified as one of the primary drivers of biodiversity loss (Emmerson et al., 2016; Dudley and Alexander, 2017; Benton et al., 2021). A long-pursued strategy to conserve biodiversity in agricultural landscapes is the increase of semi-natural habitat (SNH) size, quality, and connectivity at farm- and landscape level (Roschewitz et al., 2005; Vasseur et al., 2013). Besides these off-field conservation strategies (e.g. management of SNH), in-field strategies can be helpful and managed crop habitats could play a vital role in supporting farmland biodiversity (Sirami et al., 2019). Crop habitat in intensively farmed arable landscapes often consist of a limited number of crop types grown in large fields, nutrient-rich environments, and high levels of physical and chemical disturbance (Stoate et al., 2009; Kleijn et al., 2011, 2012). In contrast, crop production systems with high spatio-temporal crop heterogeneity can supply a diverse range of ecological habitat suitability conditions at small spatial scales throughout the season, and potentially offer an environment for diverse farmland species communities (Benton et al., 2003; Fahrig et al., 2015; Beillouin et al., 2019; Martin et al., 2019; Sirami et al., 2019; Clough et al., 2020; Wan et al., 2020).

A practical way to increase spatial crop heterogeneity is strip cropping (Ditzler et al., 2021). Strip cropping is the practice of growing different crops side by side in strips that can differ in width and length, which allows crop-specific management with standard machinery, yet

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supports ecological interactions between strips (Juventia et al., 2022). Strip cropping can influence farmland arthropod communities via two main mechanisms: (i) increased spatio-temporal availability of food and shelter (Ratnadass et al., 2012), and (ii) higher cross-habitat spillover (Tscharntke et al., 2012; Schneider et al., 2016) by increasing edge density (Martin et al., 2019). Furthermore, strip cropping may support arthropod communities during and after within-field disturbances, such as crop harvest by the presence of undisturbed strips adjoining the harvested strips. Undisturbed strips can offer nearby post-harvest micro-habitat, which might increase post-harvest survival (Sunderland and Samu, 2000), but evidence of this effect is still largely missing.

While the responses of ground-dwelling arthropods to management in large monocropped fields are relatively well studied (Marc et al., 1999; Knapp and Řezáč, 2015), studies on arthropod responses to strip cropping appeared only recently (Ditzler et al., 2021; Alarcón-Segura et al., 2022). Ditzler et al. (2021) found significantly higher spider, rove beetle, harvestmen, and non-*Pterostichus* ground beetle activity densities and species richness in organic strip cropped wheat fields of 3 and 6 m width compared to monoculture wheat fields. In contrast, ground beetles of the genus *Pterostichus* were more abundant in wheat monocultures than in wheat strips (Ditzler et al., 2021). Alarcón-Segura et al. (2022) found significantly higher spider activity density and spider species richness in conventional strip cropped oilseed rape fields of 27 and 36 m width compared to monoculture oilseed rape fields. In contrast, ground beetle activity densities and ground beetle species richness were higher in oilseed rape monocultures than in oilseed rape strip cropping fields (Alarcón-Segura et al., 2022). These studies provide valuable first insights in arthropod responses to narrow (3 and 6 m) and wide (27 and 36 m) strips over the course of the growing season of extensively managed grain and oilseed crops under organic or conventional management. However, it is not clear how sensitive ground-dwelling arthropod communities are to different strip widths in a pest-sensitive, late harvested vegetable crop and whether strips may offer refuge to arthropod communities and foster post-harvest recolonization of strips.

In this 2-year study we aimed to elucidate the effects of organic strip cropping of cauliflower and crop harvest on ground-dwelling arthropod communities. We focused on ground-dwelling arthropod communities pre- and post-harvest in a large-scale, arable experimental strip cropping field with 6, 12, 24 and 48 m wide cauliflower (*Brassica oleracea* var. botrytis) strips in the Netherlands. We asked how strip width influenced ground-dwelling arthropod activity density and community richness pre- and post-harvest. To answer this research question we used pitfall traps to assess pre- and post-harvest strip width effects on ground-dwelling arthropods. We postulated two hypotheses. Firstly, we expected that activity density and community richness of ground-dwelling arthropods is higher in narrower than in wider strips because strip cropping systems with narrower strip width enhance diversity and availability of resources at smaller spatial scales, potentially opening and broadening niches for species (Ratnadass et al., 2012; Eyre et al., 2013; Fahrig et al., 2015; Ditzler et al., 2021). Secondly, we expected that the post-harvest activity density of ground-dwelling arthropods is higher in narrower than in wider strips because of spill-over from unharvested adjoining strips adjoining harvested strips can offer post-harvest habitats and resources. The narrower strips provide post-harvest habitat at smaller spatial scales compared to wider strips (Opatovsky and Lubin, 2012; Tooker et al., 2020).

2. Materials and methods

The study was conducted on an experimental field managed by the organic arable farm *Exploitatie Reservegronden Flevoland* (ERF B.V.) in The Netherlands (52°23’37.1"N 5°20’24.6"E). The region in which the experimental field was located is characterized by intensively managed arable crop fields, field sizes of 20 ha and more, and < 2 % SNH on farms (Manhoudt and Snoo, 2003). SNH on farms in the region consisted of ditch banks, ditches, farmyards and field margins. The experimental field was 45 ha (900 m x 500 m) and consisted of a homogenous, heavy clay soil (Fluvisol on marine sediment, 28 % clay, 4.9 % soil organic matter, pH 7.1). The experimental field was bordered by a motorway, arable cropping fields and on two sides by a 20 m wide water way with trees (Fig. 1, Figure S.1.1).

2.1. Experimental lay-out

The experimental field was established in spring 2017 and our study was conducted in 2018 and 2019. Crops grown on the experimental field prior to the establishment of the experiment consisted of monocultures covering the full 45 ha field, and included red beet (*Beta vulgaris* subsp. vulgaris) in 2016 and pea (*Pisum sativum*) in 2015. To combine a wide range of strip widths representative for large-scale agriculture with a minimum level of replication, the experiment was set up as an incomplete block design with four blocks (Fig. 1). Each block consisted of two different strip widths of six crops grown side by side in strips of 6, 12, 24 and 48 m. Block 1 consisted of 12 m and 24 m wide strips, block 2 of 6 m and 24 m wide strips, block 3 of 6 m and 12 m wide strips, and block 4 of 6 m and 48 m wide strips.

Crops in block 4 were grown in shorter strips tapering to 250 m due to the field layout, and were bordered by a hedgerow and flower mixtures. The 48 m wide strips in block 4 could not be replicated due to field size constraints and served as reference treatments for large scale monocultures. In 2018, the crops consisted of potato (*Solanum tuberosum* L.), first and second year mix of grass and clover (biennial) hereafter referred to as grass-clover (*Lolium perenne/Trifolium repens*), cauliflower (*Brassica oleracea* var. botrytis), carrot (*Daucus carota* subsp. sativus), and spinach (*Spinacia oleracea*). In 2019, spinach was replaced by soy bean (*Glycine max*), and first year grass-clover was replaced by oat (*Avena sativa*) (Figure S.2.1).

Cauliflower strips of 6, 12, 24 and 48 m were used for sampling ground-dwelling arthropods pre- and post-harvest in 2018 (accession: Adamello) and 2019 (accession: Balboa). Pre-crops for cauliflower strips were potato in 2017 and grass-clover in 2018 (Figure S.2.1). Green manure crops preceding the cauliflower strips were yellow mustard (*Sinapis alba* L.) in winter 2017/2018 and second-year grass-clover in winter 2018/2019. Yellow mustard and grass-clover were terminated in February 2018 and July 2019, respectively, by 15 cm deep spading. In both years, top-soil cultivation took place one week before cauliflower planting by loosening the top 10 cm of soil, followed by seed bed preparation. Planting of the cauliflower took place early July and harvest in October (Table S.3.1). In 2019, no harvest was possible because of extreme rain which made the field inaccessible. To control cabbage white (*Pieris rapae*), the organically certified pesticide *Xentari*® (*Bacillus thuringhiensis*) was applied in September 2018 (Table S.3.1). In both years, a three meter wide annual flower strip bordered all the cauliflower strips on one side (Fig. 1; species list flower strip mixture provided in Table S.3.2). The annual flower strip was integrated in a grass-clover strip (2018) and in an oats strip (2019). On the other side the cauliflower strips were bordered by second-year grass-clover (2018) and potatoes (2019) (Fig. 1).

2.2. Arthropod sampling

The ground-dwelling arthropod community was sampled using pitfalls, from cauliflower planting (early July) to the end of the season (end of December). Three pitfalls were placed in the middle of each cauliflower strip of 6, 12, 24 and 48 m, and were spaced 10 m apart (Fig. 1). In 2018 and 2019, there were nine and five sampling rounds, respectively (Fig. 2; Table S.4.1). During the first three sampling rounds in 2018 only one pitfall trap per strip was used. Pitfall traps consisted of transparent plastic cups with an upper diameter of 8.5 cm and a depth of 14 cm. The cups were placed in the soil and were levelled with the surrounding soil surface. They were filled with 3–4 cm water plus two

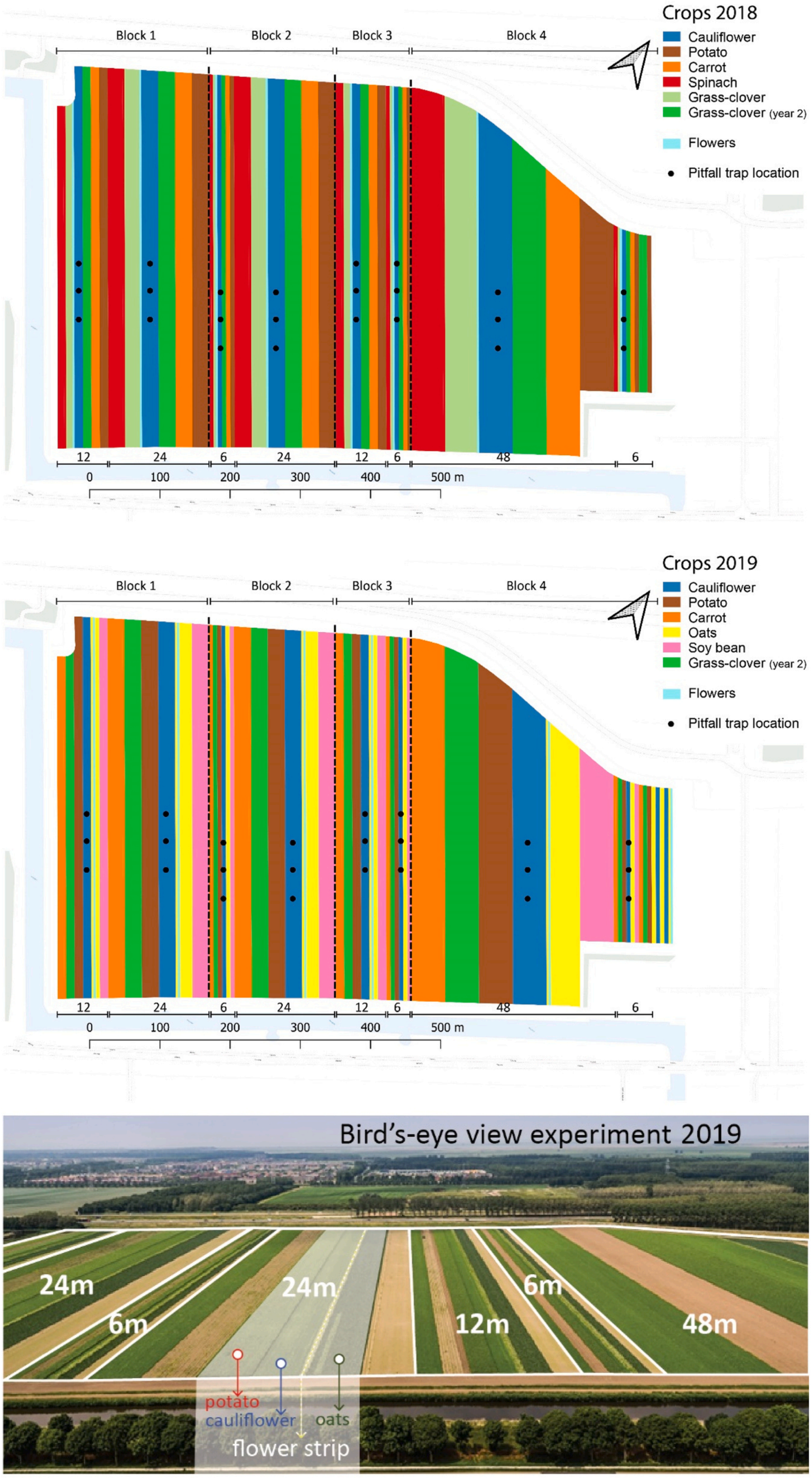

Fig. 1. Experimental layout of the strip cropping field at organic arable farm ERF B.V. in 2018 and 2019. The two maps indicate the crops in the consecutive years, the pitfall trap locations, the four blocks, and the placement of the four strip widths (6, 12, 24, 48 m). In the bird's-eye view photo of the experimental field in 2019 the position of cauliflower and its neighbors (potato and flower strip) is shown in the highlighted 24 m crop strip.

drops of odorless detergent. Each pitfall trap was covered by a black plastic roof of 12.5 cm diameter. Pitfalls were left in the field between three and eight days depending on weather conditions. A total of 168 pitfalls were placed in 2018 and 120 pitfalls in 2019. Due to farming operations three pitfalls were lost, resulting in a total of 285 pitfall samples (Table S.4.1). Sampled specimens were placed in 70 % ethanol and stored at 5°C until further processing. Specimens were categorized into six groups: (i) ground beetles (Carabidae), (ii) rove beetles

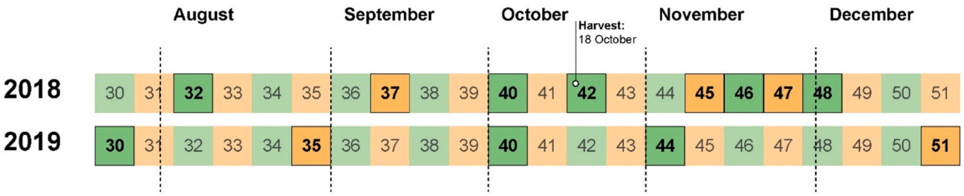

Fig. 2. Sampling rounds during the two cauliflower cropping seasons. Weeks in which sampling took place are indicated by week numbers in bold. In 2018, nine sampling rounds took place. In week 45 (2018) two successive sampling rounds were conducted within one week. In week 42 (2018) pitfalls were placed directly after cauliflower harvest. In 2019, five sampling rounds were conducted. No cauliflower harvest took place in 2019 due to extreme autumn rain. Colors indicate even (green) and uneven (orange) weeks. Full sampling date details: Table S.4.1.

(Staphylinidae), (iii) other Coleoptera families including leaf beetles (Chrysomelidae), earth-boring dung beetles (Geotrupidae) and carrion beetles (Silphidae), (iv) spiders (Araneae), (v) harvestmen (Opiliones), and (vi) centipedes (Chilopoda). Ground beetles were identified to genus resulting in seven genera. All larvae, springtails, mites, and non-ground-dwelling arthropods, including flies and lacewings were left unidentified.

2.3. Statistical analysis

Statistical analyses were performed in R (version 3.6.1) accessed through RStudio (R Development Core Team, 2020). We assessed the effects of strip width and harvest on ground-dwelling arthropod activity densities, community richness and community evenness using generalized linear mixed effect models (GLMMs). The effect of harvest could only be tested in 2018, as in 2019 no harvest was possible. We constructed a model in which strip width (6 m, 12 m, 24 m, 48 m) was included as continuous variable, harvest as a categorical two-level (before/after harvest) fixed factor, and the interaction between strip width and harvest. Block and sampling round were included as random factors. Repeated samples in the same strip were grouped via the random effect of block and round.

Since arthropod numbers differed strongly between sampling years, we analysed the data for 2018 and 2019 separately, and therefore “year” was not included as factor in the analysis. Response variables included the activity densities of the six different arthropod species groups and the eight different ground beetle genera. In addition, we included four different diversity indices as response variable: (i) total community richness was calculated as the number of unique taxa in each sample, (ii) ground beetle genera richness was calculated as the number of unique genera in each sample, (iii) total community evenness was calculated as Pielou’s evenness using the number of unique taxa in each sample *(Evenness = Shannon/log(number of taxa)),* and (iv) ground beetle genera evenness was calculated as Pielou’s evenness using the number of unique ground beetle genera in each sample (formula used as in iii). The diversity indices were calculated using the R-package *vegan* (Oksanen et al., 2015). As pitfall trap exposure in the field differed among sampling rounds, the number of days traps were kept in the field was used as a log-transformed offset variable. For all response variables we fitted: *glmm(X ∼ strip width + harvest + strip width:harvest + offset(log(fielddays)) + (1|block) + (1|round))* where *X* represents the response variable, *fielddays* the number of days of field exposure, *block* the block in which the sample was taken, and *round* represented sampling round. In 2018 > 90 % of all samples had a ground beetle Pielou’s evenness index of 0 and therefore it was not possible to do a meaningful analysis on ground beetle evenness. In the models for activity density, richness, and evenness the *strip width:harvest* interaction was only included in 2018, due to the absence of harvest in 2019. Ground beetle genera *Anchomenus* and *Blemus* were excluded from the analyses as their numbers were too low to do a meaningful analysis (three and 20 individuals collected, respectively).

For all activity density and species richness models a Poisson error distribution was used. When data was under- or overdispersed we used a generalized Poisson error distribution or negative binomial error distribution (Consul and Famoye, 1992). When models showed overparameterization due to singularity, we removed random factors ‘round’ or ‘block’ from the model (Table 1). In these models, additional caution is necessary in the interpretation of model outcomes. For all models of Pielou’s evenness a Gaussian error distribution was used. After constructing a full model, model selection based on AIC was performed using the ‘dredge’ function in the *MuMin* package (Bartoń, 2020). When multiple models had a delta AIC value of less than 2 we selected the model with the lowest AIC values which contained “strip width” as explanatory variable. We checked model assumptions by visually inspecting QQ plot residuals, and testing for goodness of fit (Kolmogorov-Smirnov test), dispersion, outliers and zero inflation, all accessed using package *DHARMa* (Hartig, 2021). To test whether any of the explanatory variables significantly explained variation in the response variables we used a Type II Wald chi-squared test using the function ‘anova’ accessed through the package *car* (Fox and Weisberg, 2018). All model estimates were back-transformed. Besides the forementioned packages we used *emmeans* (Lenth, 2021), *ggplot2* (Wickham, 2016), *ggpubr* (Kassambara, 2020), *glmmTMB* (Brooks et al., 2017), *multcomp* (Hothorn et al., 2008), and *sjplot* (Lüdecke, 2022).

3. Results

3.1. Arthropod community

We collected a total of 7196 arthropod individuals from 285 pitfall samples. In 2018, 1382 individuals were collected and 5814 individuals in 2019. The samples were dominated by ground beetles (73.7 %), followed by rove beetles (13.8 %), spiders (7.5 %), centipedes (3.5 %), harvestmen (0.6 %) and other non-Carabidae and non-Staphylinidae Coleoptera families (0.8 %). In a pitfall on average 2.7 (± 1.0) different arthropod taxa were found. The ground beetles included the following genera: *Poecilus* (49.8 %), *Pterostichus* (31.1 %), *Harpalus* (7.4 %), *Bembidion* (2.6 %), *Trechus* (1.7 %), *Blemus* (0.4 %) and *Anchomenus* (0.06 %). Seven percent of the ground beetle individuals could not be identified to genus level. The ground beetle community varied strongly between years in both activity density and community composition. Ground beetle activity density ranged from 0.4 (± 0.8) individuals/day to 6 (± 11.8) individuals/day in 2018 and 2019, respectively, whereby the activity density in round one (week 30) of 2019 was exceptionally high (24 individuals/day ± 16.6). In 2018 the ground beetle genera *Pterostichus*, *Trechus* and *Bembidion* were the most prevalent genera (together covering 73 %), whilst in 2019 *Pterostichus* and *Poecilus* were dominant (together covering 74 %). On average 1.6 (± 1.5) different ground beetle genera were found per sample.

3.2. Effect of strip width

3.2.1. Arthropod activity density

The activity density of the pooled arthropod community was not significantly influenced by strip width (p=0.111 (2018); p=0.130 (2019); Table 1). For the activity density of the pooled arthropod

Table 1

Output of final GLMM models used to test the effect of (i) strip width (6 m, 12 m, 24 m, 48 m), (ii) harvest (before/after harvest) and the (iii) strip width: harvest interaction, analyzed separately for 2018 and 2019. In 2019 no harvest was performed due to wet field conditions precluding testing arthropod responses to harvest. Error distributions (distr.), back-transformed estimates (est.), χ^2 and p-values are indicated. In the second output column (effects of harvest), estimates > 1 indicate increased activity density/richness pre-harvest compared to post-harvest and estimates < 1 indicate a decreased activity density/richness pre-harvest compared to post-harvest. Significance levels of effects were obtained by p-values resulting from Wald χ^2 tests; indicating ° $P < 0.1$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ in the response variable column if the effects of strip width were significant. All p-values indicated in **bold** indicated significant effects ($P < 0.05$) of strip width or harvest or strip width: harvest interaction.

Response variable	Distr.	Strip width			Harvest (before/after)			Strip width: harvest		
		Est.	χ^2	P(χ^2)	Est.	χ^2	P(χ^2)	Est.	χ^2	P(χ^2)
2018										
Activity density tot.	Poisson	0.999	2.542	0.111	1.555	0.521	0.470	0.983	10.965	**<0.001**
Ground beetles *	Genpois	0.994	4.218	**0.040**	7.101	17.216	**<0.001**	0.977	2.783	0.094 °
Bembidion	Poisson	0.985	2.092	0.148	-	-	-	-	-	-
Harpalus[a] ***	Poisson	0.894	11.555	**<0.001**	46.034	7.020	**0.008**	-	-	-
Poecilus[b]	Genpois	0.985	0.059	0.807	9.025	4.129	**0.042**	0.035	0.000	0.999
Pterostichus °	Poisson	0.884	3.017	**0.082**	23.529	23.570	**<0.001**	1.116	1.319	0.251
Trechus[c]	Poisson	1.004	0.214	0.644	-	-	-	-	-	-
Other genera	Poisson	1.056	1.772	0.183	17.258	1.484	0.223	0.898	2.568	0.059 °
Carabidae rich.	Genpois	0.993	2.137	0.144	2.035	33.426	**<0.001**	-	-	-
Carabidae even.[d]	-	-	-	-	-	-	**-**	-	-	-
Rove beetles	Poisson	1.001	0.061	0.802	0.653	26.964	**<0.001**	-	-	-
Spiders	Genpois	0.995	0.642	0.423	1.789	5.253	**0.022**	-	-	-
Harvestmen	Poisson	0.993	0.052	0.821	-	-	-	-	-	-
Centipedes	Poisson	1.004	0.224	0.636	0.120	5.962	**0.015**	0.969	1.771	0.184
Other coleoptera[e]	na	na	na	na	na	na	na	na	na	na
Community rich.[f] *	Genpois	0.999	4.577	**0.032**	0.887	23.335	**<0.001**	0.992	5.128	**0.024**
Community even.	Gaussian	1.001	0.647	0.421	1.039	1.588	0.208	0.993	3.614	0.057 °
2019										
Activity density tot.	Nbinom2	1.006	2.293	0.130	na	na	na	na	na	na
Ground beetles *	Nbinom2	1.011	4.752	**0.029**	na	na	na	na	na	na
*Bembidion***	Poisson	1.019	6.782	**0.009**	na	na	na	na	na	na
Harpalus ***	Poisson	0.980	17.785	**<0.001**	na	na	na	na	na	na
Poecilus	Nbinom2	1.009	0.229	0.632	na	na	na	na	na	na
Pterostichus *	Poisson	1.004	5.603	**0.018**	na	na	na	na	na	na
Trechus	Genpois	0.995	0.057	0.812	na	na	na	na	na	na
Other genera	Poisson	1.005	1.556	0.212	na	na	na	na	na	na
Carabidae rich.	Genpois	1.006	1.397	0.237	na	na	na	na	na	na
Carabidae even.	Gaussian	1.003	1.768	0.184	na	na	na	na	na	na
Rove beetles ***	Poisson	1.015	17.235	**<0.001**	na	na	na	na	na	na
Spiders[g] *	Genpois	0.988	5.002	**0.025**	na	na	na	na	na	na
Harvestmen °	Poisson	1.020	3.664	**0.056**	na	na	na	na	na	na
Centipedes	Poisson	0.998	0.017	0.896	na	na	na	na	na	na
Other coleoptera *	Poisson	0.973	4.892	**0.027**	na	na	na	na	na	na
Community rich.	Genpois	1.003	1.742	0.187	na	na	na	na	na	na
Community even.	Gaussian	1.002	0.773	0.379	na	na	na	na	na	na

[a] GLMM model without block as random variable: glmmTMB(Harpalus AD~ strip_width + harvest + strip_width*harvest + (1|round)).

[b] GLMM model without block and round as random variable: glmmTMB(Poecilus AD~ strip_width + harvest + strip_width*harvest).

[c] GLMM model without round as random variable: glmmTMB(Trechus AD~ strip_width + harvest + strip_width*harvest + (1|block)).

[d] In year one >90 % of all Carabidae sub-samples had a Pielou Evenness index of 0, preventing a meaningful analysis.

[e] In 2018 the group 'other coleoptera' was pooled with the group 'other arthropods' and hence no data of year one is for 'other coleoptera'.

[f] GLMM model without block and round as random variable: glmmTMB(Community richness ~ strip_width + harvest + strip_width*harvest).

[g] GLMM model without block as random variable: glmmTMB(Spider AD ~ strip_width + harvest + strip_width*harvest + (1|round)).

community in 2018, there was a significant interaction between strip width and harvest (p<0.001; Table 1). Before harvest, arthropod activity density was higher in narrow strips than in wide strips, while after harvest no effect of strip width was observed. For instance, arthropod activity density in narrowest strips (6 m) decreased from 1.9 individuals before to 0.9 individuals after harvest (-53 %), while the change in widest strips (48 m) was from 1.3 to 1.1 (-15 %).

The response of ground beetle activity density to strip width differed between years (Table 1; Fig. 3). Total ground beetle activity density significantly decreased with increasing strip width in 2018 (p=0.040; Table 1) and significantly increased in 2019 (p=0.029; Table 1).

The activity density of the ground beetle genus *Harpalus* was significantly negatively influenced by strip width in 2018 (p=<0.001; Table 1; Fig. 4) and 2019 (p=<0.001; Table 1; Fig. 4) and this effect was most pronounced in early season sampling rounds (Fig. 5). In contrast, activity density of *Bembidion* (p=0.009; Table 1; Fig. 4), and *Pterostichus* (p=0.018; Table 1; Fig. 4) were positively influenced by strip width in 2019. For *Bembidion* the positive response was most pronounced in the late season sampling rounds (Fig. 5).

The activity density of the non-Carabidae arthropod groups (rove beetles, spiders, harvestmen, centipedes, and non-Carabidae and non-Staphylinidae Coleoptera families) did not significantly respond to strip width in 2018 (Fig. 6). In 2019, rove beetles showed positive activity density responses to strip width (p=<0.001; Fig. 6), while spiders (p=0.025; Fig. 6) and non-Carabidae and non-Staphylinidae Coleoptera families (p=0.027; Fig. 6; all Table 1) showed negative activity density responses to strip width.

3.2.2. *Community richness*

For the arthropod community richness in 2018 there was a significant interaction between strip width and harvest (p=0.024; Table 1). Before harvest, arthropod community richness was higher in the narrower strips than in the wide strips, while after harvest, arthropod community richness was not significantly different between strip widths. Strip width did not significantly alter ground beetle richness nor ground beetle evenness (Table 1).

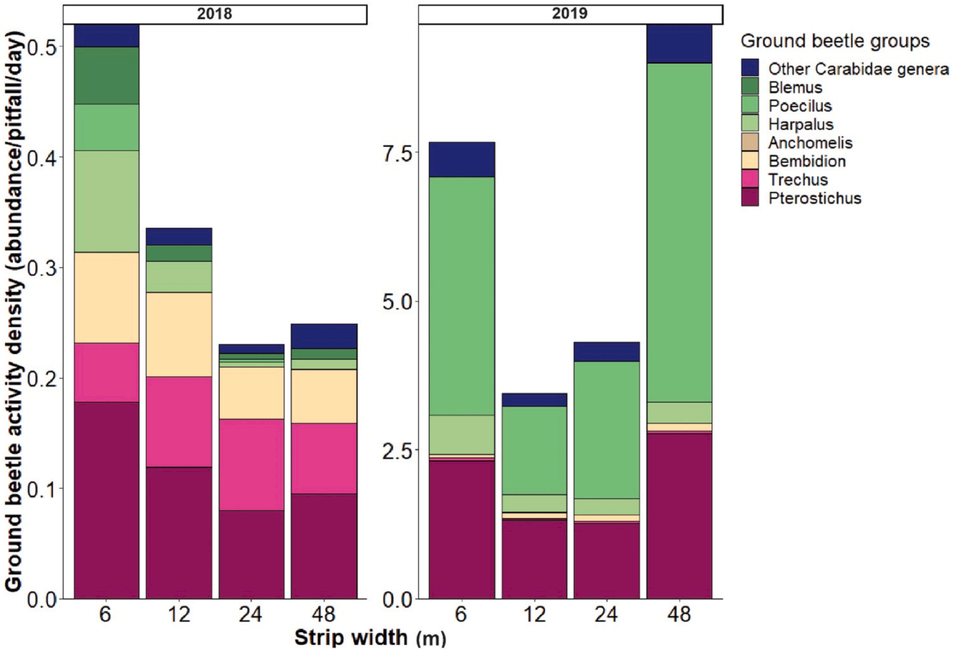

Fig. 3. Ground beetle community composition in 2018 (left) and 2019 (right). The ground beetle activity density is expressed as the number of ground beetles found per pitfall per day. Note the different Y-axis scale in 2018 and 2019.

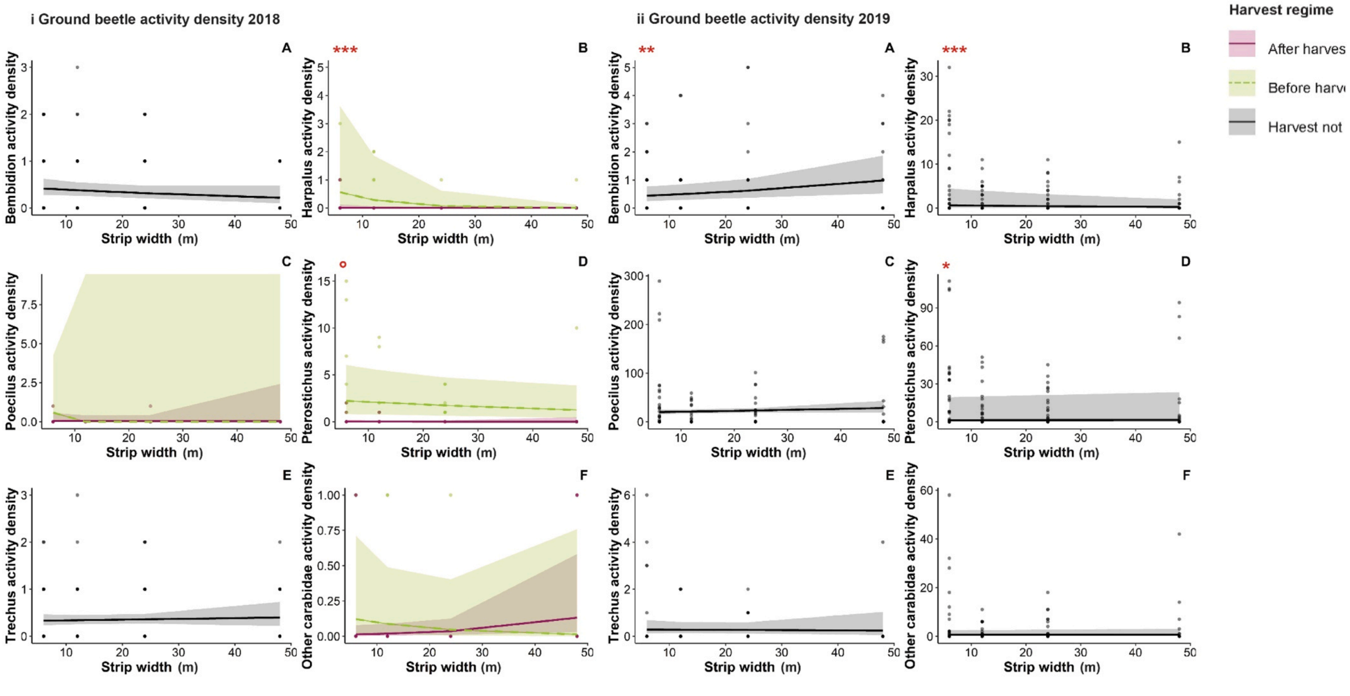

Fig. 4. Relationship between strip width and ground beetle activity density in 2018 (two left columns) and 2019 (two right columns) for Bembidion (A), Harpalus (B), Poecilus (C), Pterostichus (D), Trechus (E) and other ground beetle genera (F). Activity density is expressed as the number of ground beetle individuals per pitfall per day. Separate regressions are visualized for ground beetle activity density before (green dashed lines) and after harvest (pink solid lines), and 95 % confidence intervals are visualized in transparency ribbons around the fitted regression line. Dots indicate a sample value of an individual pitfall. Gray and black dots have a similar meaning, in case multiple sample values overlap the color of the dot is darker. In the model for Bembidion and Trechus in 2018, harvest was not selected as fixed factor in the final model. Therefore, only one relationship was visualized in panels A and E including both samples from before (Julian day 219–291) and after harvest (Julian day 292–332). In 2019, no harvest was performed due to extreme weather conditions. Results are predicted means from GLMM's as described in Table 1. Asterisks indicate significance levels: ° $P < 0.1$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

3.3. *Effect of harvest*

Ground beetles and spiders had a significantly higher activity density before cauliflower harvest (p=<0.001 and p=0.022, respectively; Table 1, Fig. 7), whilst rove beetles and centipedes had higher activity densities after harvest (p=<0.001 and p=0.015, respectively; Table 1, Fig. 7). Particularly, the activity density of the ground beetle genera *Harpalus* (p=<0.001), *Poecilus* (p=0.042) and *Pterostichus* (p=<0.001;

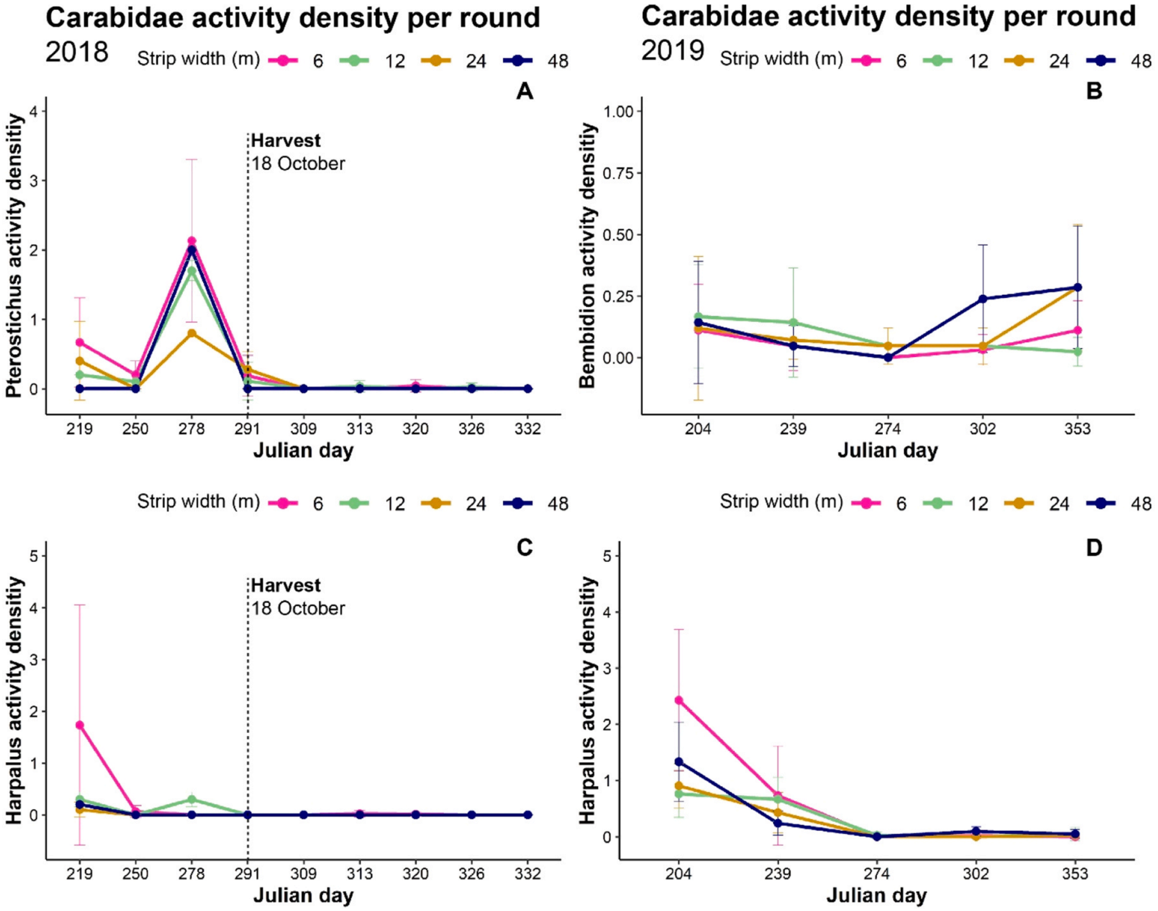

Fig. 5. Ground beetle activity densities of the genera *Pterostichus* (2018, A), *Bembidion* (2019, B) and *Harpalus* (2018 & 2019, C, D) across sampling rounds (expressed in Julian day). Harvest was only possible in 2018 and is indicated with a dotted vertical line.

Table 1) were relatively higher pre-harvest than post-harvest. The ground beetle genera richness was significantly higher pre-harvest than post-harvest (p=<0.001; Table 1).

4. Discussion

We assessed ground-dwelling arthropod community responses to strip widths of 6, 12, 24, and 48 m in cauliflower in an experimental strip cropping field. We report three key findings. Firstly, both the total ground-dwelling arthropod activity density and total ground-dwelling arthropod community richness was negatively influenced by increasing strip width, but significant effects were only observed in pre-harvest rounds in 2018. Secondly, total ground-dwelling arthropod activity density and community richness were negatively influenced by crop harvest, and this effect was not mitigated by narrow strip width. Thirdly, ground-dwelling arthropods showed group-specific responses to strip width. In the following section we will describe the specific activity density responses of ground beetles, rove beetles, and spiders, which represented 95 % of all specimens.

4.1. Effect of strip width on arthropod activity density

4.1.1. Ground beetles

In 2018, ground beetle responses were in line with our first hypothesis, but not in 2019. The negative association between ground beetle activity density and strip width in 2018 is in line with overall findings from studies on ground beetle responses to habitat diversification by applying non-crop strips (Lys and Nentwig, 1992; Lys, 1994), strip cropping (Ditzler et al., 2021; Alarcón-Segura et al., 2022), and intercropping (Wiech and Wnuk, 1991; Hummel et al., 2012). The activity density of ground beetles deviated from this trend in 2019, with negative responses to narrow strips. These year-specific responses may be explained by the different neighbouring crops (Marrec et al., 2015). In 2018, cauliflower strips were on both sides bordered by grass-clover strips (Fig. 1), which offers long-term vegetation cover (Pfiffner and Luka, 2000). The relatively high numbers of ground beetles in narrow cauliflower strips suggest that grass-clover strips act as spillover habitats for ground beetles and that spillover was more pronounced in narrow than wide neighbouring strips, in line with findings of Boetzl et al. (2019). In 2019, cauliflower strips were located next to potato and oat strips, which provide less favorable habitats for ground beetles than grass-clover, potentially reducing spill-over into cauliflower strips (Andersen, 1997). Alternatively, ground beetles may have been more strongly arrested in the narrow cauliflower strips compared to wider strips due to limited permeability of grass-clover, resulting in accumulation over time (Allema et al., 2019). While confirmation of both the spill-over effects and crop-specific entry and exit rates await experimental confirmation, our results suggest that the effects of neighbouring crops on ground beetle aggregation are more prominent in narrow than wide strip configurations.

At the ground beetle genera level, we found contrasting patterns of activity density at different strip widths. *Harpalus* responded negatively to increasing strip width in both years, while *Bembidion* and *Pterostichus* responded positively to increasing strip width in 2019. This aligns with findings of Jowett et al. (2019) who found that the activity density of *Pterostichus* species increased with increasing distance from the field edge, while an opposite pattern was found for *Harpalus*. Since *Harpalus* mainly feeds on weed seeds (Holland et al., 2009) it may have benefitted

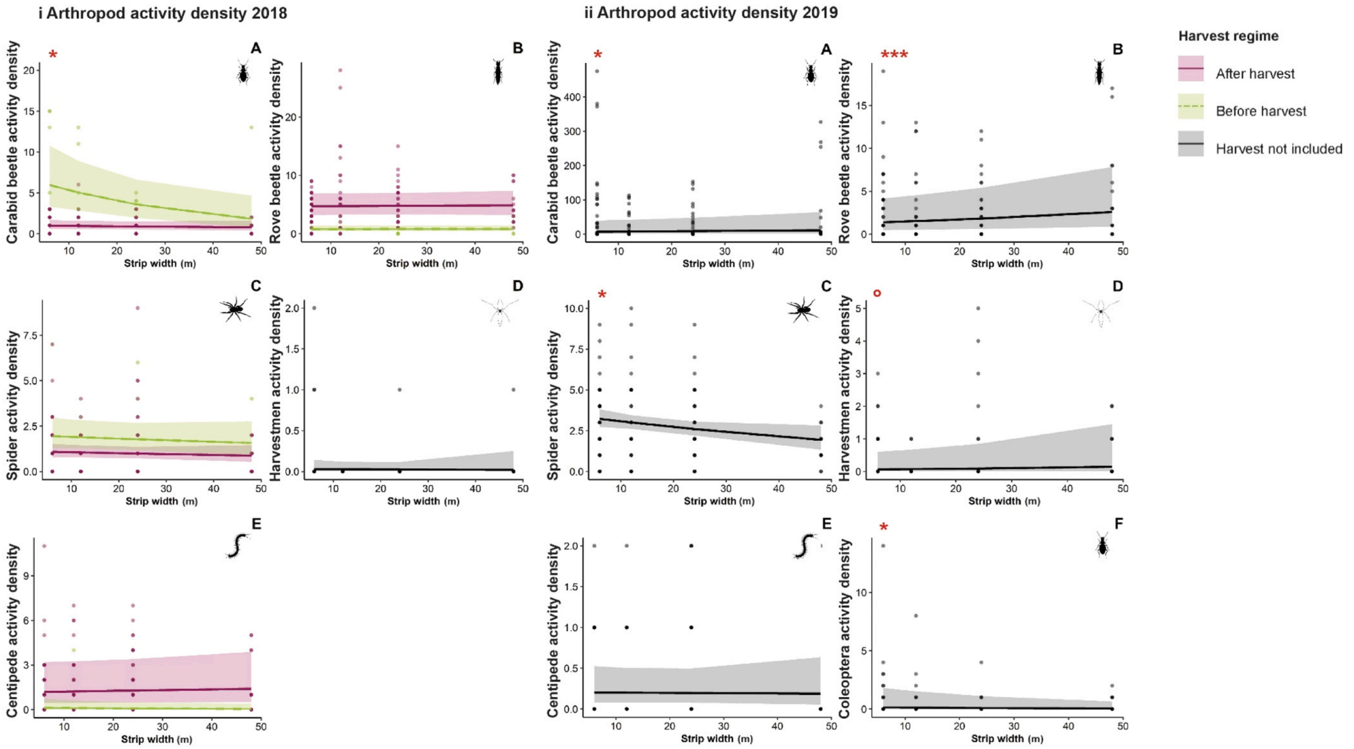

Fig. 6. Relationship between strip width and arthropod activity density in 2018 (two left columns) and 2019 (two right columns) for ground beetles (A), rove beetles (B), spiders (C), harvestmen (D), centipedes (E) and other coleoptera species (F). Other coleoptera species were not considered in 2018. Separate regressions are visualized for arthropod activity density before (green dashed lines) after harvest (pink solid lines), and 95 % confidence intervals are visualized in transparency ribbons around the fitted regression line. Gray and black dots have a similar meaning, in case multiple sample values overlap the color of the dot is darker. In the model for harvestmen in 2018 (D), harvest was not selected as fixed factor in the final model. Therefore, only one relationship was visualized in panel D including both samples from before (Julian day 219–291) and after harvest (Julian day 292–332). In 2019, no harvest was performed due to extreme weather conditions. Results are predicted means from GLMM‘s as described in Table 1. Asterisks indicate significance levels: ° $P < 0.1$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

from the a relatively high diversity of weed seeds associated with the narrow strip crop configuration (Hofmeijer et al., 2021). In contrast, the carnivorous *Bembidion* (Nilsson et al., 2016) may have benefitted from the relatively abundant prey in the wide crop strips. However, Karssemeijer et al. (2023) found no differences in *D. radicum* larvae and pupae abundance between strip cropping and monocultural cabbage fields. Amongst others, simultaneous sampling of predator and prey communities in future strip cropping experiments is necessary to gain a better understanding of genus specific responses of carabids to strip width.

4.1.2. Rove beetles

Rove beetle activity density responded positively to increasing strip width in 2019 whilst no effect of strip width was observed in 2018. Our findings are in contrast with our first hypothesis, but align with Raderschall et al. (2022) who found an increase in rove beetle activity density with increasing mean field size in a large-scale arable landscape. The abundance of rove beetles can be highly habitat and crop specific (Bohac, 1999; Rischen et al., 2021). In our study, the 6 m oat strip was not harvested in 2019, which could have supported late season prey availability, enhanced migration in the narrower crop strips compared to the wide crop strips and thus a reduced rove beetle activity density in the narrower cauliflower strips in 2019. Overall, habitat preference associated with prey availability may have influenced rove beetle community dynamics in strip crops. Assessing dispersal between strips, in combination with measuring prey availability and motility in neighboring crop strips may shed further light on the spatial dynamics of rove beetles in strip crops in future studies (Allema et al., 2015).

4.1.3. Spiders

Spider activity density was negatively associated with strip width, whilst in 2018 no significant effect of strip width on spider activity density was observed. Our finding in 2019 is in line with our first hypothesis and recent work on strip cropping showing that spider activity density responded positively to 3 m wheat strips compared to wheat monocultures (Ditzler et al., 2021) and to 27 m and 36 m oilseed rape strips compared to oilseed rape monocultures (Alarcón-Segura et al., 2022). The increase in spider activity density in narrow strips compared to wide strips in 2019 may have been caused by spill-over effects from the annual flower strip, an effect which could have decreased with increasing strip width as spider activity density is frequently linked to distance from non-crop field edges (Schmidt-Entling and Döbeli, 2009; Rischen et al., 2023). While balooning spider species are highly mobile and may colonize crops in an aerial blanket fashion (Gayer et al. (2021), the dominant spider family in our study was the non-ballooning Sparassidae (71 %), which is likely to show short distance decay responses as observed in our study. Understanding of the functional traits of spiders in terms of habitat preferences and dispersal mode can help to interpret spider responses to strip crop configurations.

4.2. Effect of strip cropping on arthropod community richness and ground beetle genera richness

Arthropod community richness responded negatively to strip width in 2018. This observation was in line with our first hypothesis, yet this response was only observed in 2018 in the pre-harvest sampling rounds. We did not find differences in ground beetle genera richness between strip widths. Our findings on ground beetle genera richness contrast with reports of decreasing ground beetle species richness in agricultural fields with increasing distance from a field edge, bordering for example flowering fields (Boetzl et al., 2019; Jowett et al., 2019). A possible

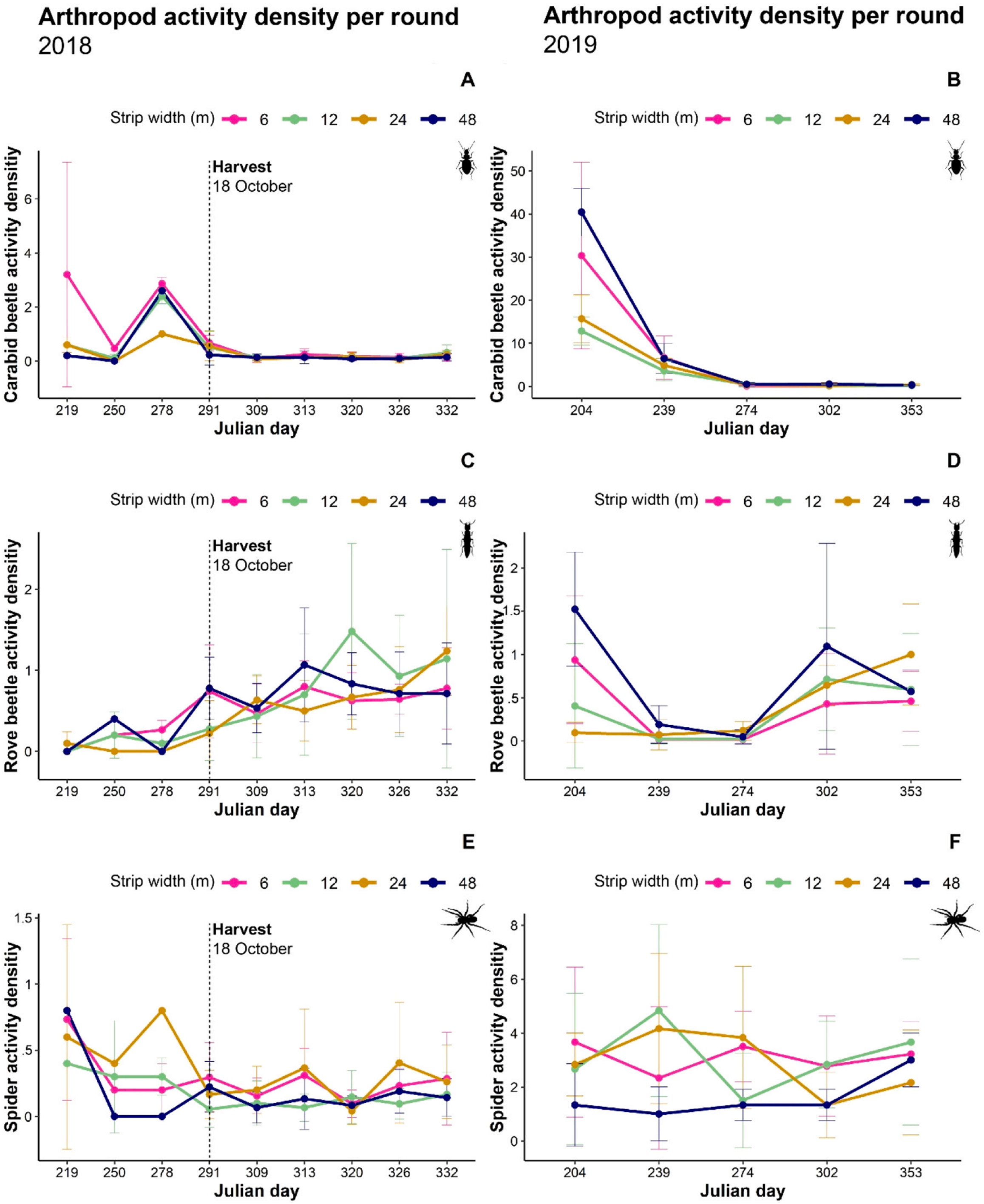

Fig. 7. Mean activity density of carabid beetles (A, B), rove beetles (C, D) and spiders (E, F) across sampling round (expressed as Julian day) in 2018 (A, C, E) and 2019 (B, D, F). Harvest was only possible in 2018 and is indicated with a dotted vertical line.

explanation of the contrasting findings between our study and other studies is that most of the studies on distance decay and edge-effects used non-crop edges in their experimental design. Non-crop edges may provide refuge, breeding and hibernation habitat that annual crop strips do not provide (Thomas et al., 2002). When comparing our work with recent work on ground beetle responses to strip cropping we see similar limited distance decay effects as found in our study. For instance, Alarcón-Segura et al. (2022) found no effect of strip cropping on ground beetle richness in the flowering period of oilseed rape, and mixed effects of strip cropping on ground beetle richness in the flowering period of wheat. Ground beetles are polyphagous predators of which many species are well adapted to conditions in agricultural landscapes (Holland and Luff, 2000). Possibly the crop combinations in our study did not offer enough resources to attract species from outside the field to significantly increase ground beetle richness in arable fields. This reasoning also applies to the ground-dwelling arthropod community richness. Potentially, richness is improved in the field early on in the season, however, this is not sustained throughout the season. Furthermore, shifts in ground beetle richness and community composition might only become visible after several years post-establishment (MacLeod et al., 2004). A strategic integration of permanent, within-field non-crop habitat in strip cropping designs might be necessary to support diverse ground beetle populations in strip cropping fields. A longer term, multi-year sampling regime and a ground beetle identification to species level may be necessary to study species accumulation in strip cropping fields.

4.3. Effect of harvest on arthropod activity density and community richness

Harvest impacted specific species groups differently. The activity density of rove beetles was higher after harvest, while it was lower for spiders and ground beetles. Declines of spider communities after wheat crop harvest have been reported earlier (Opatovsky and Lubin, 2012) and were associated with the deterioration of micro-habitat due to vegetation cover removal (Cuff et al., 2021) and direct mortality due to mechanical disturbance (Thorbek and Bilde, 2004). Furthermore, observed harvest effects might also be due to changes in season and temperature. Our findings did not confirm our second hypothesis that narrow strip width increases post-harvest recolonization rates of ground-dwelling arthropods by the provision of suitable micro-habitat in the strip adjoining the harvested crop strip (Sunderland and Samu, 2000). In 2018, when harvest effects could be tested the adjoining crop on both sides of the cauliflower strips was grass-clover. Post-harvest arthropod populations may have dispersed into the grass-clover strips finding shelter and suitable overwintering habitat (Cuff et al., 2021), but this mechanism still needs to be confirmed by more detailed assessments.

4.4. Limitations of the study

Our study had at least three limitations. First, it was not possible to include a replicate of the 48 m strip width in the experimental field, constraining the statistical power of our analysis. Second, while we assessed the effect of cabbage harvest on arthropods activity density in 2018, this was not possible in 2019 due to extremely wet field conditions. Third, specimens were identified at functional group level, preventing to assess species specific responses to strip width and harvest. Although these limitations hamper the generalization or rigor of our findings, our main interest was to test strip cropping in a realistic large-scale farm setting to generate actionable knowledge for farmers. We therefore focused on the information that is of interest of farmers, including the maximum strip width for which meaningful effects can be expected, and the general responses of arthropods to strip cropping, rather than the responses of specific taxa. Our co-learning approach with farmers reflects the challenge to develop an approach that can generate both scientific rigorous and practically relevant information, and this comes with strengths (e.g., inclusion of a 48-m strip) and weaknesses (e.g., limited replication and taxonomic resolution).

5. Conclusions

We found that in general narrower strip width affected the ground-dwelling arthropod community positively in terms of overall community richness and spider activity density. However, rove beetle and ground beetle activity density varied in their responses depending on year, which may be related to previous or neighboring crops, and responses to strip cropping were often species groups or genera specific. Despite this variation, our study provides a proof of principle that increasing crop heterogeneity in large-scale fields can have general net-positive outcomes for arthropod community richness and activity density of certain species groups without taking land out of production. By applying strip cropping, farmers can make a positive contribution to biodiversity conservation in agricultural landscapes whilst retaining their productivity and use of large scale farm machinery. However, we did not find evidence that strip cropping can also enhance short-term post-harvest crop recolonization by arthropods. Further development of strip cropping designs is needed to further optimize crop combinations and integration of less disturbed elements.

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CRediT authorship contribution statement

Dirk F. van Apeldoorn: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bas Allema:** Writing – review & editing, Investigation, Formal analysis. **Fogelina Cuperus:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Walter A.H. Rossing:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Felix J.J.A. Bianchi:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fogelina Cuperus and Dirk van Apeldoorn report financial support was provided by the Dutch Ministry of Agriculture, Nature and Food Quality. Walter Rossing reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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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.2024.109137.

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