"THREE-STRIP MANAGEMENT": INTRODUCING A NOVEL MOWING METHOD TO GENERATE ARCHITECTURAL COMPLEXITY IN PERENNIAL FLOWER MARGINS TO BETTER SUPPORT POLLINATORS

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Abstract—Flower margins are widely adopted as agri-environment measure (AEM) to enhance farmland biodiversity. However, perennial flower margins need appropriate mowing schemes to manage succession, especially in regions with high nitrogen depositions, and current schemes inadequately address the needs of arthropods, including pollinators. Effective management should provide floral diversity with staggered flowering times, creating varied sward structures for diverse habitats that support shelter, nesting, and mating sites.

To address these challenges, a novel mowing method, called 'Three-strip management,' is proposed. This method involves dividing the margin into three strips using curved instead of straight mowing lines. During each cycle, one third remains unmown for shelter, while clippings are removed to lower soil nutrient status and reduce succession. The use of overlapping curved mowing lines aims to maximize variety in patterns, fostering spatio-temporal variation in the (re)growth of perennials and swards. Unlike Regular rotational management, multiple uneven parts are kept unmown over winter, increasing the number of subzones in different mown states over successive years.

In this study, field trials comparing Three-strip management with Regular rotational management reveal positive effects especially during the second year, including higher bee abundance and diversity. Plant-pollinator networks also demonstrate increased interactions. While the study focuses on bees, the potential of the Three-strip management to support other beneficial insects is discussed. Given declining insect populations in agricultural landscapes, this paper offers insights into enhancing perennial flower margins as AEM to support pollinator populations. The novel Three-strip management presents a promising strategy for balancing management needs with diverse insect requirements, contributing to sustainable biodiversity conservation in agricultural settings.

Keywords—Three-strip management, perennial flower margins, uneven mowing, curved mowing lines, spatio-temporal variation, pollinators

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INTRODUCTION

Over the past decades, in agricultural landscapes, land-use change has had a significant negative impact on terrestrial agrobiodiversity, which has contributed to the decline of many insect populations (Tscharntke et al. 2005; Hellwig et al. 2022). Here, intensification of agricultural production may be the key driver, with higher levels of pesticide use, and artificial fertilizers, negatively impacting insect populations such as pollinators (Stoate et al. 2001; Goulson et al. 2015). The use of fertilizers in farmland can be a direct source of excessive nitrogen (N), but atmospheric N depositions are also contributing (Dupre et al. 2010). While pesticides can have a direct impact on insect populations, excessive N reduces plant diversity, therefore decreasing habitat quality. Excessive N encourages grasses, rather than pollinator host plants like flowering dicots that provide food (pollen and nectar) and shelter. (Stevens et al. 2004; Cole et al. 2020). This situation is found in many regions of Northern to Central Europe, including Belgium, The Netherlands, Northern France and the UK (Dupre et al. 2010; Kooijman et al. 2017). While the effect is largely seen and reported in grassland ecosystems (e.g. Stevens et al. (2004)), it also plays an important role when other agri-environment measures (AEM) are being implemented, such as perennial flower strips in farmland. Such AEM can support populations of pollinators including bees and other beneficial insects (Decourtye et al. 2010; Scheper et al. 2015; Brittain et al. 2022; Hellwig et al. 2022; McHugh et al. 2022).

Flower margins are increasingly being installed throughout Northern Europe as a popular AEM to help support insect populations such as pollinators that are currently under pressure in farmland. International programs are set up to promote these measures such as the BEESPOKE project in the North Sea Region of Europe (BEESPOKE 2019). However, because of excessive N as mentioned above, installation alone is not enough and management is also needed, especially for perennial flower strips. Conventional mowing schemes for perennial flower margins are being used to remove excess cuttings resulting from N excess in the environment (Zhang et al. 2017) and to prevent them from turning into homogenous grass margins with almost no flowering perennials remaining for pollinators (McHugh et al. 2022). Conventional schemes usually consist of mowing the entire strip once per season, or spreading over two mowing cycles (mostly between late June to early July and late September to the end of Autumn), with mowing dates also depending on local directives or legislation (Garbuzov et al. 2015).

With regards to the mowing technique, the method and type of machinery used is also important. While flail mowing is still used more frequently for margins when compared to rotary and cutter bar mowing, it is a less effective management option. Flails cut the mown parts into tiny pieces negatively impacting the survival of inhabiting invertebrates (Wynhoff et al. 2011), with average mortality rates reporting up to 60% (Humbert et al. 2009). Besides, due to the flail mowing process, small cut pieces degrade faster and are decomposed by the soil microbial environment into nutrient rich compounds which contain readily available N (Liang et al. 2014). This steadily favours grass growth over flowering dicots, even after one mowing cycle (Unpublished results and pers. comm. Arjen Strijkstra, VHL University of Applied Sciences, The Netherlands). While rotary mowers showed a relative reduction in invertebrate mortality by an average of 37%, a more severe negative effect on arthropod survival rate is noted when a conditioner is used; a conditioner is a machine that mechanically crushes the grass immediately after mowing to accelerate the drying process. The lowest mortality is reported with the application of double bladed cutter bars (Humbert et al. 2009; Humbert et al. 2010). Rotary mowing without a conditioner, on the contrary, has a more positive effect on arthropod survival, with an up to threefold lower mortality rates for invertebrates after a mowing cycle, especially when in combination with hay making or removal of the cuttings (Humbert et al. 2010; Nichols et al. 2022b). Yet, every mowing cycle still has a destructive impact on inhabiting arthropods such as pollinators. Therefore, in alternative management schemes the entire margin is not mown at once, but late or phased mowing is applied. Thus, only a rectangular part of the margin is mown during each mowing cycle and in most cases the cut parts are removed, with a positive impact on flowering plant species, and food provisioning for pollinators (Broyer et al. 2016; Jones et al. 2017).

Phased mowing of rectangular zones in the margin is better than the whole area being mowed simultaneously, however, taken over one year, mostly such successive phased mowing schemes applied in the same season still led to the entire margin being fully mown. Hence, during one year's season, few overwintering zones remain in the margin. Unmown zones are composed of taller tussocks and forbs, generated from senesced inflorescences of dicots, old grasses and grass-like plants. These old structures contribute to biotic and abiotic variation of the margin, such as microclimatic variation and shelter. Overwintering structures are important supporting arthropod diversity, especially when accompanied by a higher complexity of forb structures. A study on meadow butterflies that compared different grass margin types along road verges, found that both nectar abundance and shelter provided by tall overwintering vegetation structures were important factors (Saarinen et al. 2005). The positive impact of overwintering sward complexity on arthropod diversity has also been reported in other studies including for beetles (Woodcock et al. 2007) and bees (Potts et al. 2009).

A recent study on high nature value grasslands found that the spatio-temporal complexity generated by management practices was the determining factor in the long-term maintenance and conservation of diversity and species composition (Kun et al. 2021). A new management method was proposed for grasslands to enhance the intrinsic diversity by applying a variable mowing pattern in time and space, called "Sinus management" (Couckuyt et al. 2015; Parmentier & Van Kerckvoorde 2021). Here, spatial variation in mowing due to the application of a variable mowing line is the basic idea generating spatio-temporal variation in forb structures and habitat complexity, and thus to enhance inhabiting pollinator diversity. Therefore, and based on these insights, I here present a novel and practical management method for perennial flower margins installed as AEM in farmland. Through spatio-temporal variation in mowing management, habitat complexity for pollinating insects is enhanced. The method has been tested in the field and initial results of two years of testing are presented comparing this new method with Regular (late) mowing on such margins.

Introducing "Three-strip management" as novel management technique

In this study, the "Three-strip management" for perennial flower margins is introduced. When traditional late mowing on margins is applied, only a long straight part of the margin is mown while the unmown part can be regarded as shelter for inhabiting fauna (Broyer et al. 2016). Contrary to this, variable Three-strip management does not use straight mowing lines but curved, 'meandering' lines instead. These meandering mowing lines create variable areas of mown and unmown subzones of the margin after each mowing cycle. For each subsequent mowing cycle, another curved mowing line is applied, and importantly, this line does not follow the previous mowing line, but rather crosses into the previous one to generate maximum irregularity in mowing patterns. Fig. 1 illustrates the stages of three successive mowing cycles of the novel method starting from an unmanaged margin (applied in this study between end of June 2021 and end of September 2022). As the curved mowing lines are different each mowing cycle, over one season some parts are kept unmown, while others are mown only once or twice. Thus, the mowing complexity increases each year with parts that are mown differently, including unmown zones, always mown zones and an increasing variety of intermediates. Hence, the basic idea behind this mowing method is that there is increased variation in the growing cycle of perennials (and grasses) which generates prolonged flowering during the season. For example, species like *Leucanthemum vulgare* and *Centaurea jacea* bloom in spring and at the beginning of summer, respectively. However, if these perennials are cut at the end of June (first cut), generally they regrow and give new shoots to bloom again later in the season (e.g. until the end of September). Due to the patchy mowing conditions, there is a greater chance that plants of the same species will have different (re)growing conditions next to each other in the margin to prolong their flowering period. Additionally, the variable growing conditions results in more diverse swards and tussocky structures, contributing to variable microclimates and shelter conditions for arthropods. These are examples of potential positive impacts of the Three-strip mowing management in comparison to a regular management with straight mowing lines. Flowering variation, sward diversity and microclimatic complexity are increasingly recognized as important parameters to better support pollinator diversity (Corbet et al. 1993; Woodcock et al. 2007; Scheper et al. 2015; Galpern et al. 2021; Kun et al. 2021; Tölgyesi et al. 2022).

To implement the novel Three-strip management practically in a season with two cuts (one mid June – early July and a second cut mid September – early October), the margin can be subdivided into three imaginary smaller strips longitudinally, hence the name, and then two variable curved cutting lines can be drawn varying between the inner borders of the imaginary strips. When implementing the novel mowing method on newly installed margins, it is best to have them sown the previous year (end of Autumn until beginning December) to allow perennials to fully develop before the first cut. Also, the cutting height should not be too low, advisably a

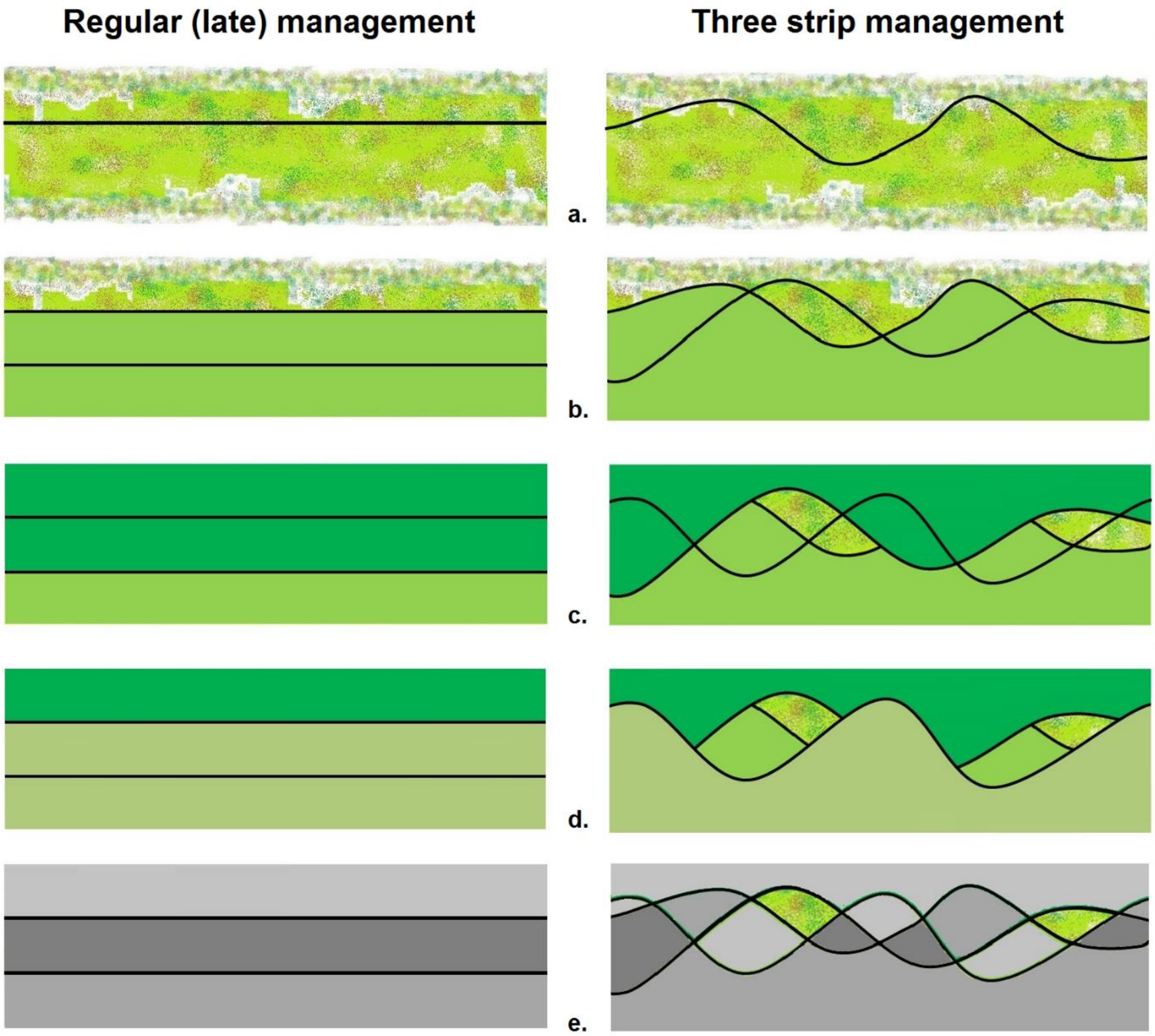

Figure 1. The effect of three successive mowing cycles illustrated on a margin when either Three-strip or Regular management is applied. a. first mowing line starting from an unmown grass margin or perennial flower strip. The margin is divided into three equal subzones longitudinally. When applying three-strip management, a curved instead of straight mowing line is used; b. Result after first mowing cycle in the first season, normally applied end of June, and drawing of second mowing line; c. Result after second mowing cycle, normally applied end of September, and drawing of third mowing line; d. Result after third mowing cycle; e. Overlay and general result after three mowing cycles illustrated.

minimum cutting height of approximately 10 cm (4 inch) should be applied. Importantly, while the mowing lines are variable, the mown to unmown areas are fixed to approximately 2:1. In the field, these curved mowing lines represent the two mowing cycles in that season. Predefined mowing maps can be loaded into the GPS driving system of the mowing machinery making it easier for contractors to control and execute. It is important to mention that the cut and uncut part of the curved mowing line should be alternated each mowing cycle with the process repeated each year.

MATERIALS AND METHODS

STUDY SITES AND MARGINS

We selected five locations in the provinces of East- and West-Flanders (Flanders, Belgium) and in each location two paired study sites (in total ten sites) were established, as represented in Fig. 2. Study sites within one location consisted of two perennial flower margins and their size was equal within each location (all study sites within a width of 10 ± 5 m and length of 75 ± 25 m). Flower

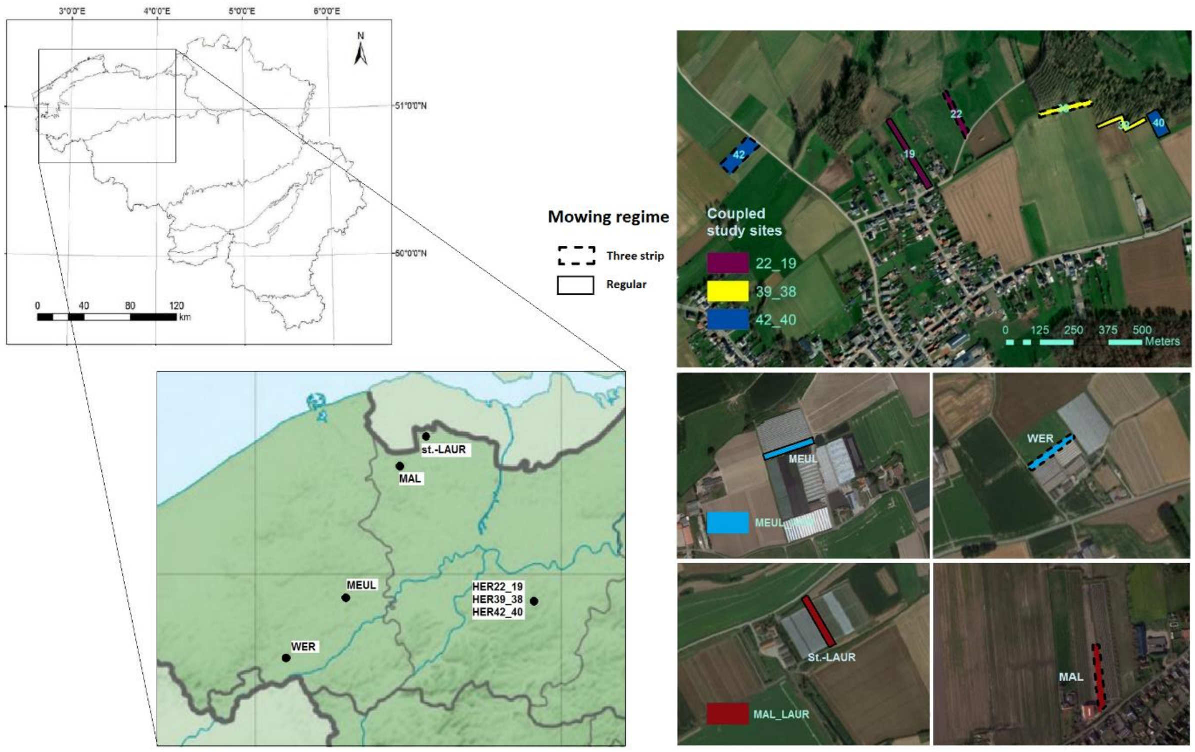

Figure 2. Locations & study sites selected. Each of the five locations with two paired flower margins with either Three-strip or Regular management applied. Margin contour lines indicate management regimes applied: Dashed line = Three-strip management, Full line = Regular management. Abbreviations: HER = Herzele, LAUR = Sint-Laureins, MAL = Maldegem all situated in East -Flanders; MEUL = Meulebeke, WER = Wervik, situated in West-Flanders (Flanders, Belgium).

margins were situated in an arable environment surrounded by a landscape matrix of small landscape elements (SLE). These included hedgerows, solitary trees or tree rows, gardens as well as paved elements such as streets and buildings. As SLE harbour source populations of pollinators that can be attracted and supported by the installed margins (Montero-Castano & Vila 2012; Senapathi et al. 2017), we ensured that surrounding landscapes of paired study sites within a location were similar. Margins consisted of perennial flowers intermixed with a minimal amount of grasses (*Poaceae* spp.) that were not included in the seed mixes but arose spontaneously. Compositions of the margins are given in Table 1. Margins with perennials were sown between Autumn 2019 (two locations) and Spring 2020 (three locations) and thus installed at least one full season prior to the start of the experiment (conducted from spring 2021 to Autumn 2022). All margins were managed with conventional management and regarded as fully developed, before they were divided into one of the two management groups. Conventional management prior to the start of the experiment in Spring 2021 consisted of mowing half of the margin in June (between end of June and beginning of July) and a full mowing in September (mid to late September), following straight mowing lines, with rotary mowers (cutting passes with a mowing width between 1.5 and 2.5 m, depending on the location) and removal of clippings after each mowing cycle.

Mowing management methods

This study used a paired study design, comparing the Three-strip management with Regular management on perennial flower margins. The novel management was executed as described above. Regular late mowing (or rotational) management was performed as follows: during each mowing cycle two thirds of the margin were mown as rectangular subzones (longitudinal direction) and one third was kept unmown. For both the Three-strip and Regular mowing study sites the percentage of mown to unmown surface was kept equal for each margin, i.e., 2:1 at every mowing cycle. For each location

Table 1. Composition of perennial flowers mixes in all margins used as study sites in this study monitored during the second year of management. Numbers are given in percentages. R = Regular management; 3S = Three-strip management.

Study site	HER40	HER42	HER19	HER21	HER38	HER39	MEUL	WERV	ST-LAUR	MALD
Management	R	3S	R	3S	R	3S	R	3S	R	3S
Daucus carota	14	14	10	10	10	10	14	14	14	14
Anthriscus Sylvestris	0	0	10	10	10	10	11	11	0	0
Achillea millefolium	8	8	3	3	3	3	3	3	8	8
Centaurea cyanus	18	18	0	0	0	0	0	0	18	18
Centaurea jacea	14	14	0	0	0	0	0	0	14	14
Matricaria chamomilla	6	6	0	0	0	0	0	0	6	6
Trifolium pratense	6	6	8	8	10	10	8	8	6	6
Trifolium repens	6	6	0	0	2	2	2	2	6	6
Lotus corniculatus	14	14	14	14	15	15	13	13	14	14
Tanacetum vulgare	8	8	0	0	0	0	0	0	8	8
Leucanthemum vulgare	0	0	15	12	15	15	13	13	0	0
Medicago lupulina	0	0	8	6	8	8	8	8	0	0
Ranunculus acris	0	0	7	7	7	7	7	7	0	0
Prunella vulgaris	0	0	9	9	9	9	8	8	0	0
Crepis capillaris	4	4	0	0	0	0	2	2	4	4
Veronica Chamaedris	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0	0
Hypericum perforatum	0	0	0.5	0.5	0.5	0.5	0	0	0	0
Poaceae spp.(grasses)	2	2	15	20	10	10	10	10	2	2

the mowing was conducted within two days using the same type of cutting machinery (rotary cutter, cutting passes with a mowing width between 1.5 and 2.5 m, depending on the location), both for the first cutting (between end of June and to beginning of July) and the second one (mid to late September). All cuttings were removed during a period good weather. After each Three-strip mowing cycle, the cuttings were removed within ten days of mowing in all sites; cuttings removal was achieved by first mechanically heaping in windrows before removing them from the margin. The cut and uncut part of the mown and unmown zone within each study site was alternated each mowing cycle, over one season generating a full mown margin under the Regular management, while under the Three-strip management some variable unmown parts typically remain. Consequently, only the effect of the variable curved mowing line (Three-strip management) was tested versus the uniform straight mowing line (Regular rotational management) and other parameters were kept fixed. Prior to mowing, the extent of each mown study site was made equal by drawing the mowing patterns onto a map of the margin. This pattern was then transferred to each study site by GPS, before mowing was started.

After selection of paired study sites in 2021, all sites were 'baseline' monitored prior to the start of implementing the two different management regimes. The first cycle of Three-strip versus Regular management was done between the end of June-mid July 2021, and the second one at the end of September that year. The same mowing periods were kept during the next season, generating a total of four mowing cycles by the end of 2022. The effect of four successive mowing cycles with either three or Regular management is illustrated in Fig. 1. Fig. 3 illustrates the mowing process in year two (2022) of Regular mowing along straight mowing lines in comparison with the uneven mowing process of the Three strip management.

POLLINATOR AND FLORISTIC SURVEYS

The effect of the two management types on pollinator assemblages was tested, with a focus on bees in this study. All bee taxa were monitored

Figure 3. Illustrating the execution of the Three-strip versus Conventional mowing management. Results are shown in year two (2022) including a. Conventional mowing along straight mowing lines (dashed lines) with one third kept unmown, and b. the uneven mowing process with curved lines of the Three strip management showing the three zones (dashed lines), mowing after a curved mowing line, and the clippings concentrated in windrows ready to be removed.

including honeybees, bumblebees and solitary bees. Bees were monitored using area-time counts over the entire margin with a fixed duration and each survey consisted of 2 rounds of 30 ± 5 min effective monitoring conducted on the same day, one before and one after 1:30 pm., and all monitoring was conducted between 10:00 am. and 6:00 pm. (Westphal et al. 2008; Barkmann et al. 2023). Rounds were chosen randomly over the full margin. Monitoring was conducted only during appropriate weather conditions (low wind speed, temperature above 18 degrees, and not on cloudy days). For each individual bee observation, the flowering plant was recorded. Bee specimens were determined in the field, if possible, or put in coded tubes for identification to species level in the lab. Bees under the *Bombus terrestris* complex were aggregated and included *Bombus terrestris, Bombus lucorum* and *Bombus cryptarum*. During each monitoring round, the abundance of flowering plants was scored at the margin level using a Tansley scale (Tansley 1946).

Baseline monitoring occurred prior to the start of the mowing experiment between April and end of June 2021 to check for bias in bee assemblages in all locations between coupled study sites (prior to random attribution to either 'Three-strip' or Regular' management). The baseline monitoring consisted of three to four survey rounds in total. After the first mowing cycle, monitoring each margin continued. In the first year of the experiment, three to four survey rounds were achieved from the end of June until mid September in 2021, and in 2022 from mid May until mid September.

ANALYSIS AND STATISTICS

The effect of management type on bee assemblages was investigated each year, with a focus on alpha diversity indices, i.e. number of bees (Counts), number of bee species (Richness) and bee diversity (Shannon Diversity). All data analyses were conducted in R version 4.2.2 (R Core Team 2021). Bee richness and diversity were calculated with the package vegan (Oksanen et al. 2016). After checking residual plot diagnostics and normality of the dataset (Shapiro-Wilk test in R), Linear mixed-effect (LMERs) or Generalised linear mixed-effect models (GLMMs) were used to test for the impact of management type on bee Counts, Richness and Diversity. GLMM Models were fitted using the maximum likelihood (Laplace Approximation) method, using the lme4 package for the LMERs and GLMMs (Bates et al. 2015). All residuals of non-Gaussian models were checked by fitting a negative binomial and Poisson family, but residual plots showed that all models best fitted with a Poisson error distribution. Models were tested for overdispersion using the dispersion test in the AER package (Kleiber & Zeileis 2008; Kleiber & Zeileis 2019), and all final models were not overdispersed. The Bayesian Information Criterion (BIC), being a more conservative test than the Akaike's information criterion (AIC), was used to select the best final model (i.e. that with the lowest score) (Dziak et al. 2020). In all models, management type (two levels: Three-strip versus Regular) was used as a fixed factor. Location/Site and sampling Period were included as random factors. Shannon's Diversity index was also calculated for the flowering plant diversity (abundance estimations based on Tansley scores for each study site and survey conducted) and included as an explanatory variable in each model to improve model fit (Nichols et al. 2022a). All analyses were performed for the T0, 2021 and 2022 datasets separately, to test for a bias prior to the installation of either management type, and to test the yearly differences that were intrinsically introduced and built up through the experimental set up with differences in mowing methods between the Three-strip and Regular management.

To identify the effect of mowing management regimes after three successive mowing cycles (second season) on flowering plants and bees visiting them, a plant-pollinator network analysis was performed. Therefore, bee visits to each flowering species in the margins were pooled according to management treatment based on the 2022 dataset. To assess the level of dependence of the flowering plant community on a given pollinator in the network" (Bascompte & Jordano 2007), their species strength was also calculated. 'Species strength' is defined as the sum of dependencies (proportion of visits) of flower visitors relying on a specific plant species, and was calculated on the pooled survey data using the 'strength' function in the *bipartite* package (Dormann 2011). As a result, a discrimination between the proportions of highly and less frequently visited flowering plants in the plant-pollinator network was visualized for each management type using the 'computeModules' and 'plotWeb' functions. The difference in abundance of visited plants by bee species between the two management types was also visualized as a matrix using the 'VisWeb' function in the same *bipartite* package in R (Dormann et al. 2008).

RESULTS

BASELINE MONITORING (T0)

In total, 1043 bees encompassing 20 bee species were observed during the baseline survey, of which there were 924 individual bumblebees, 97 honeybees, and 22 solitary bees. To exclude a bias in bee assemblages being incorporated in the study design, the effect on alpha diversity metrics was tested between the two groups of study sites. No significant differences were observed for count of bees, bee diversity and bee richness between study sites in all locations (All P values > 0.05) Fig. 4. Thus, all locations were retained for further analysis.

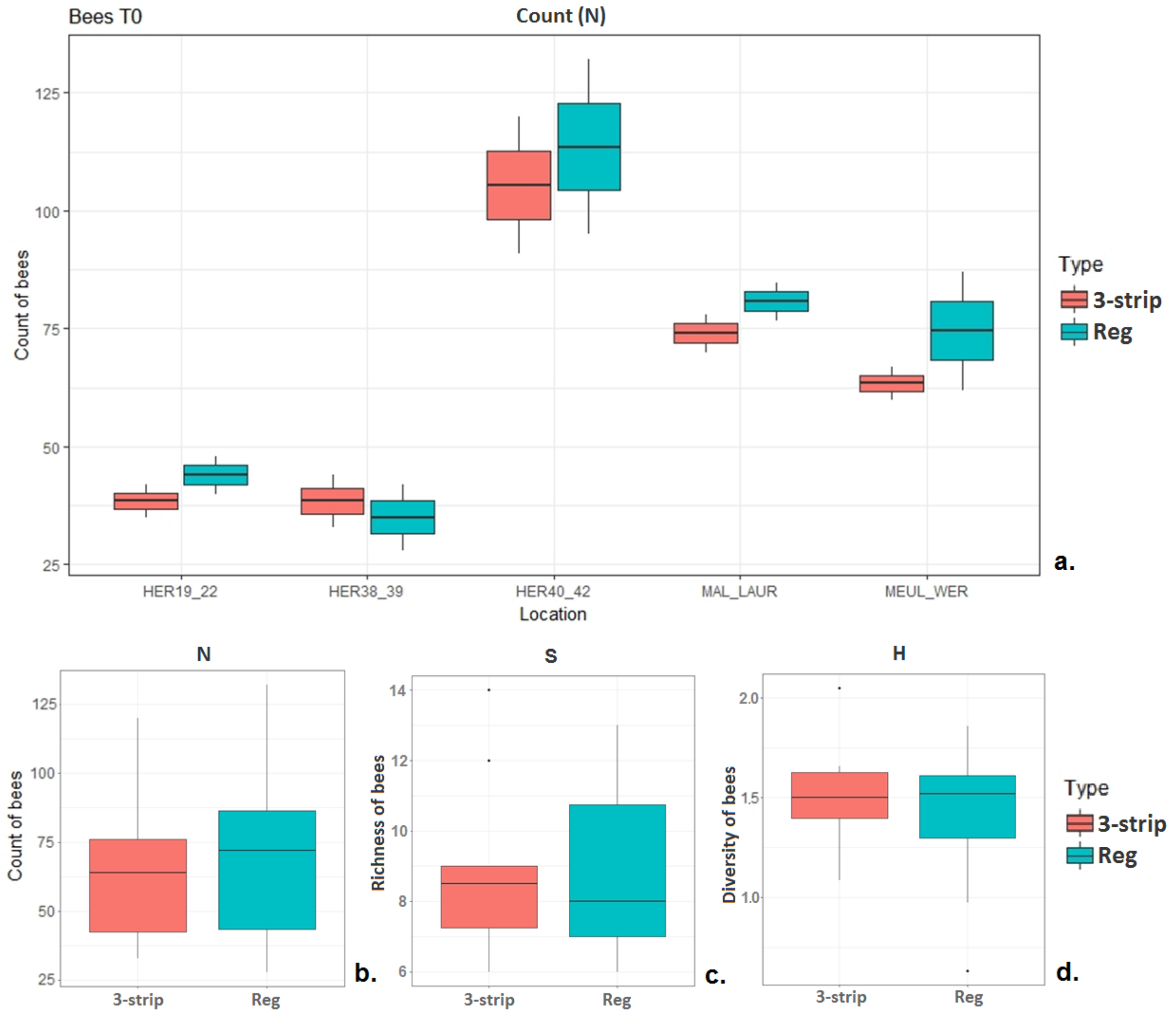

Figure 4. Baseline monitoring effect of all coupled study sites on alpha diversity indices. a.-b. bee counts (Count), c. bee diversity (Diversity) and d. bee richness (Richness) per management type. Count data is represented for each location and are merged per management type. No significant effects were observed.

First and second year of Three-strip versus Regular management (2021-2022)

In 2021, after the first mowing cycle, 1581 bees were counted, 903 in the Three-strip and 678 bees in the Regular managed study sites, with subgroups of honeybees (388 versus 171), bumblebees (446 versus 455), and solitary bees (69 versus 52), respectively. Analysis of bee counts showed a positive effect for the margins with Three-strip management, but this was only marginally significant (Z = -1.98, P = 0.047) Supplementary Fig. S1. Looking to other alpha diversity parameters, a higher number of bee species (bee richness, S) was observed when applying the Three-strip management (14 species Regular versus 20 species Three-strip management), but this effect was not significant (Z = -1.14, P = 0.26); also bee diversity (H) followed the same trend (T = -1.23, P = 0.22).

During the second year (2022), and after three successive mowing cycles, the effect on total bee assemblages was more pronounced Fig. 5. A total of 922 bees were counted, 550 and 372 bees in the Three-strip versus Regular managed study sites, respectively. Analysis of bee counts showed a clear positive effect for the Three-strip management (Z = -4.45, P < 0.001). Looking to other alpha diversity parameters, higher numbers of bee species were found (bee richness) when applying the Three-strip management (11 species Regular versus 15

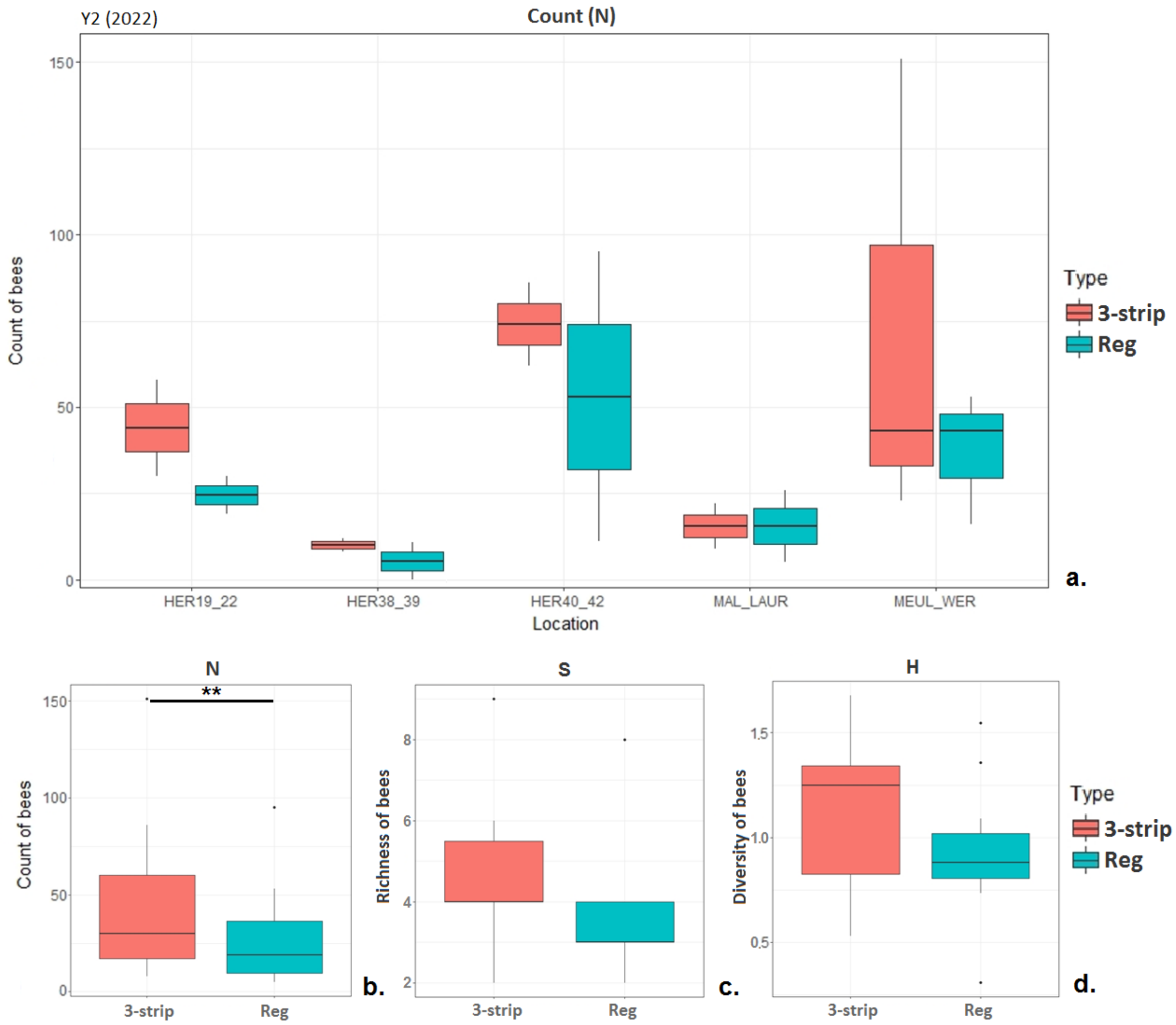

Figure 5. Effect after two seasons of Three-strip management versus Regular management on alpha diversity indices. a.-b. bee counts (Count), c. bee diversity (Diversity) and d. bee richness (Richness) per management type. Count data is represented for each location and are merged per management type. ** indicates a significant effect at α = 0.001

species Three-strip management), but this effect was again not significant (Z = -1.15, P = 0.25). Bee diversity (H) followed the same trend but now the effect was just on the boundary of not significant at the α = 0.10 significance level (T = -1.57, P = 0.11).

IMPACT OF MANAGEMENT TYPE ON PLANT-POLLINATOR NETWORKS

Here, I considered the 2022 data only, as the effect of management on bee assemblages was most pronounced in the second year. This effect is shown in Fig. 6, with a matrix representation (using a log (x+1) scale) showing the frequency of all plant-pollinator visitations observed. This shows that the Three-strip management generated a higher total number of interactions (45 versus 35), observed through common bee species interactions, as well as a higher numbers of unique plant-pollinator interactions, driven by solitary bee species. The plant-pollinator networks for Three-strip management and the Regular management sites combined over five sites and four collecting dates is also visualized in Suppl. Fig. S2. The proportions of common flower visits and flower visits relying on a specific plant are indicated in black and green, respectively. When comparing the two networks, it is seen that for the Three-strip management the most common bees (*Apis mellifera, Bombus pascuorum, Bombus lapidaries and Bombus terrestris* complex) generated more interactions, mostly on *Lotus corniculatus, Ranunculus acris/ R. repens, Vicia villosa, Trifolium pratense* and *T. repens* (black proportions), but also

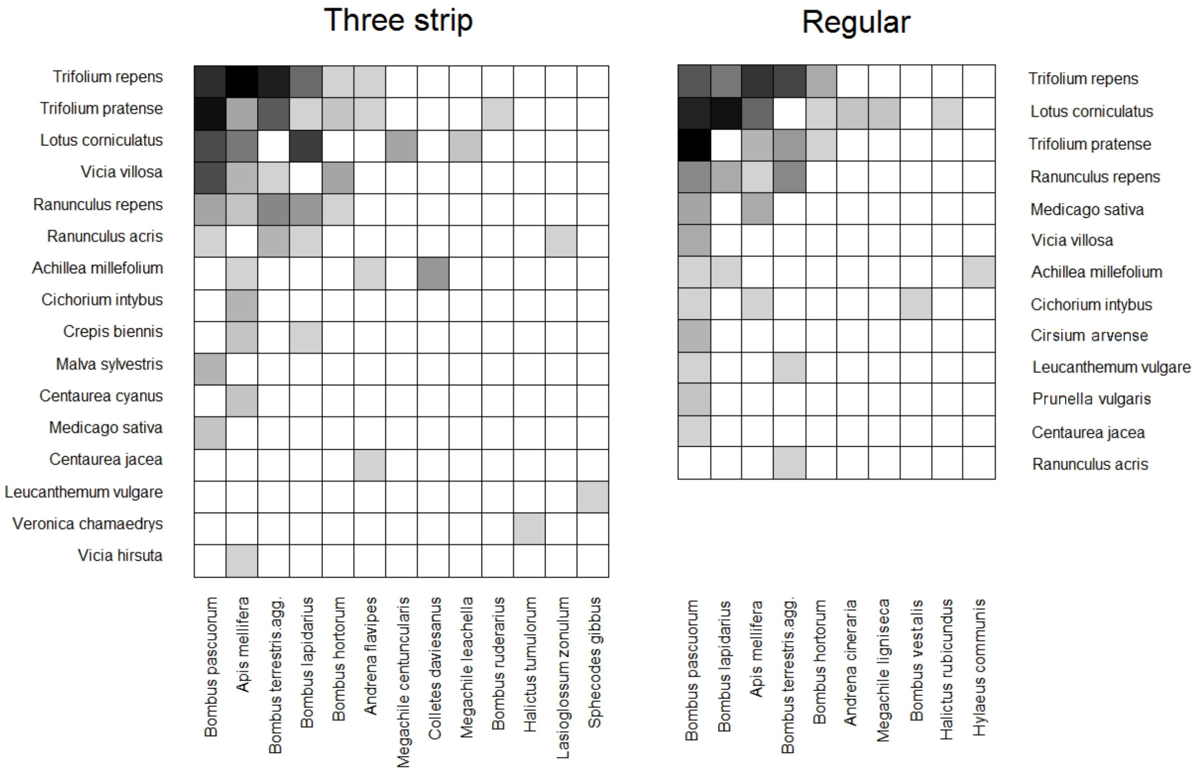

Figure 6. Abundance visitation matrix for the two management methods tested. Matrix showing the effect of the Three-strip management (left) versus Regular management (right) mowing method on the abundance of all plant-bee interactions. Bee species are displayed in columns and plants in rows. The grey to black rectangles show observed interactions with more frequent interactions shown by a darker colour.

that the rarer solitary bees generated more unique interactions on a higher number of visited plant species (green proportions).

Discussion

Effect of management on pollinator assemblages

While establishing wildflower strips in farmland is a popular measure for boosting flowers and supporting pollinators, appropriate forb heterogeneity (Jiang & Hitchmough 2022; Nichols et al. 2022b). In this study the impact on bee assemblages of a novel Three-strip management in comparison with Regular management was investigated in perennial flower margins. It was seen that especially after the second mowing season a significantly greater number of bees were counted in the Three-strip management, and also a positive trend on bee diversity was observed. Looking to different bee functional groups, social bees, including *A. mellifera, B. pascuorum, B. lapidarius* and those under the *B. terrestris* complex, were more supported by the Three-strip management compared to Regular management. While the management of perennial flower margins is often forgotten. This, leads to a fast degradation in floral species diversity and abundance, and neglects the wider needs of pollinators such as habitat complexity providing more diverse resources such as food and shelter (Woodcock et al. 2007; Goulson et al. 2008). Thus, ideal management regimes should include regular mowing, and removal of cuttings to optimize floral diversity and to enhance

Regular management was also attracting these common bee species, the linear mowing pattern (generating more uniform blocks of forbs and perennials flowers) seems to be less attractive compared to the uneven cuts with subzones spread over the margin generated by the Three-strip management (Fig. 3). Besides, based on the total number of solitary bees counted (as subgroup), mostly found under the genera *Lasioglossum, Andrena, Hylaeus* and *Megachile,* a positive effect of the Three-strip management was seen. This was less pronounced (also for the Regular management) when comparing with numbers of social bees (i.e. *Bombus* and *Apis*). Here, an explanation can be found in that common social bees are more mobile with higher average flight distances compared to solitary bees (Walther-Hellwig & Frankl 2000; Gathmann & Tscharntke 2002). Moreover, social bees are more common in farmland, and thus could be more easily found in the most attractive margins compared to the less mobile and rarer solitary bee species.

Little research is available comparing the effect of mowing management techniques of margins on bee functional groups and diversity indices. Yet, when looking at the total bee assemblages, a comparison can be made with restoration studies. For example, a US study dealing with restoration management through canopy thinning in remnant and post-agricultural woodlands showed that effects on bee abundance were more apparent than effects on diversity (Simpson's diversity index) (Breland et al. 2018). Here, it was also observed that bee abundance was the fastest responding parameter of the metrics investigated. Looking to other bee indices, no effect was found on bee richness in this study. However, the total number of species was rather low in both management types over the two seasons considered (28 in Three-strip versus 20 in Regular management margins). The latter observation is not unexpected as the margins were all situated in agro environments, missing small landscape elements of high nature value supporting a high diversity of solitary bee species as a source population (Stoate et al. 2001; Scheper et al. 2015; Senapathi et al. 2017). Therefore, the potential impact could be masked by considering the total bee diversity of which most are solitary bees. Also, only two years were investigated, and the positive trend on bee richness may become more apparent in subsequent years. Expanding the study to a longer-term trial and in a diverse landscape is needed to fully investigate the potential of the Three-strip management on diversity indices of bee communities.

Additionally, the seed mix sown in the margins in this study may not be fully optimized to attract a great number of solitary bees. Recently it has been shown that novel, optimized seed mixes attract a greater number of bee species (Nichols et al. 2022a). Alternatively, the novel Three-strip management, compared to Regular rotational management, may show a significant effect on total bee numbers, but not on bee richness.

Nevertheless, having greater numbers of bees observed after only two years of different mowing regime is a positive outcome for farmers; especially if insect-pollinated crops are cultivated in close proximity to Three-strip managed margins. Common bees over rarer ones (Kleijn et al. 2015) are major pollinators of commercially important crops such as rapeseed, field beans, pumpkins, sunflowers, and many fruits such as apple and pear, as well as other crops (Garibaldi et al. 2013; Kleijn et al. 2015; Isaacs et al. 2017; Bänsch et al. 2020).

Effect of management on plant-pollinator networks and bee diversity

When comparing plant-pollinator networks in Three-strip versus regularly managed margins, the most common bees (*Apis mellifera, Bombus pascuorum, Bombus lapidaries and Bombus terrestris* complex) generated the highest interaction rates in the Three-strip management, mostly on *Lotus corniculatus, Ranunculus acris/ R. repens, Vicia villosa, Trifolium pratense* and *T. repens*. Solitary bees, on the other hand, generated more unique interactions visiting a higher number of plant species. Yet, when comparing the proportions of plants visited by the different bee species (Suppl. Fig. S2) and the species composition of the seed mixes sown (Table 1), some of the flowering plants are more attactive than others, with a difference between species groups, i.e. honeybees and bumblebees, and solitary bees. A recent UK study investigating sown flower margin compositions and attractiveness for wild bees found that only 11 'key' wildflower species were required to cater to all wild bee species recorded during their study, only eight of which were sown species (Nichols, Holland & Goulson 2022). Of these species, *Taraxacum officinale* agg., *Cirsium vulgare*, and *Daucus carota* received the highest visits of wild bee species (Nichols et al. 2022a), which is partly in agreement with the observations in this study. In this study it was found that honeybees and bumblebees predominantly foraged on clovers belonging to the Fabaceae and Leguminosae, while solitary bees were more frequently found foraging on Asteraceae species. This is generally in agreement with Nichols et al., (2022a), who reported that bumblebees were mainly seen on Fabaceae species (29.7%), Asteraceae species (27.9%), and Papaveraceae (26.0%), whereas solitary bee visits were heavily focused on

Asteraceae species (58.9%), followed by Apiaceae (12.4%) (Nichols et al. 2022a).

It was also observed that the Three-strip management generated a higher number of interactions involving common bee species, as well as a higher number of unique plant-pollinator interactions, driven by solitary bee species. This is an important observation as this may indicate that the Three-strip management is generating more diverse resource conditions for a greater number of bees. In contradiction to this, it is reported that when social bees are in greater abundance, competition for food resources will exist between social bees (especially honeybees) and solitary bees (Sugden et al. 1996; Steffan-Dewenter & Tscharntke 2000; Geslin et al. 2017; Meeus et al. 2021). However, food resources are not the only resource bees need, and variation in nesting, shelter and mating places are important (Westrich 2018; Cole et al. 2020; Galpern et al. 2021; Kovács-Hostyánszki et al. 2021). Such variation could be generated by the three-strip management. Such additional bee resources were not investigated in depth in this study. However, the observation that both polylectic social bees and oligolectic solitary bees can be attracted in higher numbers, as well as observed on more plant species, may indicate that the Three-strip management is generating a more diverse habitat structure for bees. This rationale aligns with a study investigating mutualistic plant-pollinator networks (Bastolla et al. 2009). They reported that the structure of mutualistic networks determines the number of coexisting species, and that the nested architecture of real mutualistic networks increases their biodiversity (Bastolla et al. 2009). Therefore, the spatio-temporal variation in curved mowing is likely to generate a more diverse, interconnected structure in the flower margin that reduces competition and better supports diverse pollinator communities. Hence, while a direct link between other resources was not investigated in this study, this novel management is likely to enhance the availability of a variety of resources supporting a range of bee taxa, each having their specific requirements.

Effect of an optimally managed flower margin in the landscape

For pollinating bees, their different needs (food including nectar and pollen, shelter, breeding places) can best be provided at landscape level. This is provided by a variety of small landscape elements (SLE) that can be found in biodiverse and bee supporting landscapes (Schweiger et al. 2005; Meyer et al. 2017; Galpern et al. 2021). While SLE such as hedgerows, gardens, trees and shrubs, amongst others, can complement wildflower margins in meeting these needs, ideally the margin itself is also contributing to all components needed by the different stages of a diverse array of bees. Especially for less mobile insects, such as small solitary bees, these components are best provided in the vicinity of the food resources (Peeters et al. 2012). In agreement with this, a UK study testing the effect of mowing intensity on grass margins found that, while the effect on flower species richness was less impacted by mowing intensity, especially the unmown, taller grasses were more attractive for flower-visiting insects compared to more frequently mown zones (Garbuzov et al. 2015). Therefore, with regards to novel mowing regimes, it is partcularly important that at least part of the margin or flower strip is kept unmown during the whole season. Additionally, during the overwintering period these unmown zones provide nesting places for all bees, including soil nesting, above-ground and cavity nesting species.

While in this study the Three-strip management method was tested on bee assemblages only, this novel management could also support other insect groups. Non-bee pollinators also require suitable resources for larvae, such as host plants for caterpillars (Curtis et al., 2015). Generating spatio-temporal variation of a variety of resources in the margin is likely to create better habitat conditions for other important pollinator groups including butterflies and syrphids (Pywell et al. 2004; Garrido et al. 2022), as well as beneficial insects (predators for crop pests). Next to this, better managed margins could act as corridors between semi-natural habitat elements and enhance the total heterogeneity in the landscape (Senapathi et al. 2017). Future studies on this novel management method are needed to untangle these questions and also further investigate the impacts on bee and other insect assemblages after multiple years.

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DISCLOSURE STATEMENT

The author declares no potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data of this study are published as supplementary material together with the online version of this article (Appendix II. Plant-bee observations of T0, Y1 and Y2). Please contact the corresponding author for data requests.

APPENDICES

Additional supporting information may be found in the online version of this article:

Appendix I. Supplementary Fig. S1. Effect after one year of different management method on alpha diversity indices

Appendix I. Supplementary Fig. S2. Plant-pollinator networks after three successive mowing cycles (year 2022)

Appendix II. Plant-bee observations of T0, Y1 and Y2

REFERENCES

Bänsch S, Tscharntke T, Ratnieks FLW, Härtel S, Westphal C (2020) Foraging of honey bees in agricultural landscapes with changing patterns of flower resources. Agriculture, Ecosystems & Environment 291:106792. https://doi.org/10.1016/j.agee.2019.106792

Barkmann F, Huemer P, Tappeiner U, Tasser E, Ruedisser J (2023) Standardized butterfly surveys: comparing transect counts and area-time counts in insect monitoring. Biodiversity and Conservation 32:987-1004. https://doi.org/10.1007/s10531-022-02534-2

Bascompte J, Jordano P (2007) Plant-animal mutualistic networks: The architecture of biodiversity. Annual Review of Ecology, Evolution, and Systematics 38: 567-593. https://doi.org/10.1146/annurev.ecolsys.38.091206.095818

Bastolla U, Fortuna MA, Pascual-Garcia A, Ferrera A, Luque B, Bascompte J (2009) The architecture of mutualistic networks minimizes competition and increases biodiversity. Nature 458:1018-1020. https://doi.org/10.1038/nature07950

Bates D, Machler M, Bolker BM, Walker SC (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67:1-48. https://doi.org/10.18637/jss.v067.i01

BEESPOKE (2019) Benefitting Ecosystems through Evaluation of food Supplies for Pollination to Open Knowledge for End users. Interreg program, cofunded by the European Union, NSR

Breland S, Turley N, Gibbs J, Isaacs R, Brudvig L (2018) Restoration increases bee abundance and richness but not pollination in remnant and post-agricultural woodlands. Ecosphere 9:e02435. https://doi.org/10.1002/ecs2.2435

Brittain C, Benke S, Pecze R, Potts SG, Peris-Felipo FJ, Vasileiadis VP (2022) Flower Margins: Attractiveness over Time for Different Pollinator Groups. Land 11:1933. https://doi.org/10.3390/land11111933

Broyer J, Sukhanova O, Mischenko A (2016) How to sustain meadow passerine populations in Europe through alternative mowing management. Agriculture, Ecosystems & Environment 215:133-139. https://doi.org/10.1016/j.agee.2015.09.019

Cole LJ et al. (2020) A critical analysis of the potential for EU Common Agricultural Policy measures to support wild pollinators on farmland. Journal of Applied Ecology 57:681-694. https://doi.org/10.1111/1365-2664.13572

Corbet SA et al. (1993) Temperature and the pollinating activity of social bees. Ecological Entomology 18:17-30. https://doi.org/10.1111/j.1365-2311.1993.tb01075.x

Couckuyt J, Cuvelier S, Parmentier L (2015) Sinusbeheer: een nieuw maaibeheer op maat van dagvlinders en insecten. Flemish Entomological Society (VVE WG DV), Antwerpen

Decourtye A, Mader E, Desneux N (2010) Landscape enhancement of floral resources for honey bees in agro-ecosystems. Apidologie 41:264-277. https://doi.org/10.1051/apido/2010024

Dormann C, Gruber B, Fründ J (2008) Introducing the bipartite Package: Analysing Ecological Networks. R News 8:8-11

Dormann CF (2011) How to be a specialist? Quantifying specialisation in pollination networks. Network Biology 1:1–20

Duprè C, Stevens CJ, Ranke T, Bleeker A, Peppler-Lisbach C, Gowing DJG, Dise NB, Dorland E, Bobbink R, Diekmann M (2010) Changes in species richness and composition in European acidic grasslands over the past 70 years: the contribution of cumulative atmospheric nitrogen deposition. Global Change Biology 16:344–357. https://doi.org/10.1111/j.1365-2486.2009.01982.x

Dziak JJ, Coffman DL, Lanza ST, Li RZ, Jermiin LS (2020) Sensitivity and specificity of information criteria. Briefings in Bioinformatics 21:553-565. https://doi.org/10.1093/bib/bbz016

Galpern P, Best LR, Devries JH, Johnson SA (2021) Wild bee responses to cropland landscape complexity are temporally-variable and taxon-specific: Evidence from a highly replicated pseudo-experiment. Agriculture, Ecosystems & Environment 322:107652. https://doi.org/10.1016/j.agee.2021.107652

Garbuzov M, Fensome KA, Ratnieks FLW (2015) Public approval plus more wildlife: twin benefits of reduced mowing of amenity grass in a suburban public park in Saltdean, UK. Insect Conservation and Diversity 8:107-119. https://doi.org/10.1111/icad.12085

Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C, Carvalheiro LG, Harder LD, Afik O, Bartomeus I, Benjamin F, Boreux V, Cariveau D, Chacoff NP, Dudenhöffer JH, Freitas BM, Ghazoul J, Greenleaf S, Hipólito J, Holzschuh A, Howlett B, Isaacs R, Javorek SK, Kennedy CM, Krewenka KM, Krishnan S, Mandelik Y, Mayfield MM, Motzke I, Munyuli T, Nault BA, Otieno M, Petersen J, Pisanty G, Potts SG, Rader R, Ricketts TH, Rundlöf M, Seymour CL, Schüepp C, Szentgyörgyi H, Taki H, Tscharntke T, Vergara CH, Viana BF, Wanger TC, Westphal C, Williams N, Klein AM (2013) Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance. Science 339:1608–1611. https://doi.org/10.1126/science.1230200

Garrido P, Naumov V, Soderquist L, Jansson A, Thulin CG (2022) Effects of experimental rewilding on butterflies, bumblebees and grasshoppers. Journal of Insect Conservation 26:763-771. https://doi.org/10.1007/s10841-022-00420-4

Gathmann A, Tscharntke T (2002) Foraging ranges of solitary bees. Journal of Animal Ecology 71:757-764. https://doi.org/10.1046/j.1365-2656.2002.00641.x

Geslin B et al. (2017) Massively Introduced Managed Species and Their Consequences for Plant-Pollinator Interactions. In: Bohan DA, Dumbrell AJ, Massol F (eds) Networks of Invasion: Empirical Evidence and Case Studies, vol 57. Elsevier Academic Press Inc, San Diego, pp 147-199. https://doi.org/10.1016/bs.aecr.2016.10.007

Goulson D, Lye GC, Darvill B (2008) Decline and conservation of bumble bees. Annual Review of Entomology 53:191-208. https://doi.org/10.1146/annurev.ento.53.103106.093454

Goulson D, Nicholls E, Botias C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347:1255957. https://doi.org/10.1126/science.1255957

Hellwig N, Schubert LF, Kirmer A, Tischew S, Dieker P (2022) Effects of wildflower strips, landscape structure and agricultural practices on wild bee assemblages – A matter of data resolution and spatial scale? Agriculture, Ecosystems & Environment 326:107764. https://doi.org/10.1016/j.agee.2021.107764

Humbert JY, Ghazoul J, Sauter GJ, Walter T (2010) Impact of different meadow mowing techniques on field invertebrates. Journal of Applied Entomology 134:592-599. https://doi.org/10.1111/j.1439-0418.2009.01503.x

Humbert JY, Ghazoul J, Walter T (2009) Meadow harvesting techniques and their impacts on field fauna. Agriculture, Ecosystems & Environment 130:1-8. https://doi.org/10.1016/j.agee.2008.11.014

Isaacs R, Williams N, Ellis J, Pitts-Singer TL, Bommarco R, Vaughan M (2017) Integrated Crop Pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent crops. Basic and Applied Ecology 22:44-60. https://doi.org/10.1016/j.baae.2017.07.003

Jiang MY, Hitchmough JD (2022) Can sowing density facilitate a higher level of forb abundance, biomass, and richness in urban, perennial "wildflower" meadows? Urban Forestry & Urban Greening 74:127657. https://doi.org/10.1016/j.ufug.2022.127657

Jones L et al. (2017) Can on-site management mitigate nitrogen deposition impacts in non-wooded habitats? Biological Conservation 212:464-475. https://doi.org/10.1016/j.biocon.2016.06.012

Kleiber C, Zeileis A (2008) Applied Econometrics with R, New York. https://doi.org/10.1007/978-0-387-77318-6

Kleiber C, Zeileis A (2019) AER: Applied Econometrics with R

Kleijn D, Winfree R, Bartomeus I, Carvalheiro LG, Henry M, Isaacs R, Klein A-M, Kremen C, M'Gonigle LK, Rader R, Ricketts TH, Williams NM, Lee Adamson N, Ascher JS, Báldi A, Batáry P, Benjamin F, Biesmeijer JC, Blitzer EJ, Bommarco R, Brand MR, Bretagnolle V, Button L, Cariveau DP, Chifflet R, Colville JF, Danforth BN, Elle E, Garratt MPD, Herzog F, Holzschuh A, Howlett BG, Jauker F, Jha S, Knop E, Krewenka KM, Le Féon V, Mandelik Y, May EA, Park MG, Pisanty G, Reemer M, Riedinger V, Rollin O, Rundlöf M, Sardiñas HS, Scheper J, Sciligo AR, Smith HG, Steffan-Dewenter I, Thorp R, Tscharntke T, Verhulst J, Viana BF, Vaissière BE, Veldtman R, Ward KL, Westphal C, Potts SG (2015) Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. Nature Communications 6:7414. https://doi.org/10.1038/ncomms8414

Kooijman AM, van Til M, Noordijk E, Remke E, Kalbitz K (2017) Nitrogen deposition and grass encroachment in calcareous and acidic Grey dunes (H2130) in NW-Europe. Biological Conservation 212:406-415. https://doi.org/10.1016/j.biocon.2016.08.009

Kovács-Hostyánszki A, Soltesz Z, Szigeti V, Somay L, Báldi A (2021) Non-rotational set-aside fields improve reproductive success of cavity-nesting bees and wasps at the landscape scale, but have no effect on other wild bees and hoverflies in mid-summer. Agriculture, Ecosystems & Environment. 308:107255. https://doi.org/10.1016/j.agee.2020.107255

Kun R, Babai D, Csathó AI, Vadász C, Kálmán N, Máté A, Malatinszky Á (2021) Simplicity or complexity? Important aspects of high nature value grassland management in nature conservation. Biodiversity and Conservation 30:3563–3583. https://doi.org/10.1007/s10531-021-02262-z

Liang ST, Grossman J, Shi W (2014) Soil microbial responses to winter, legume cover crop management during organic transition. European Journal of Soil Biology 65:15-22. https://doi.org/10.1016/j.ejsobi.2014.08.007

McHugh NM, Bown B, McVeigh A, Powell R, Swan E, Szczur J, Wilson P, Holland J (2022) The value of two agri-environment scheme habitats for pollinators: Annually cultivated margins for arable plants and floristically enhanced grass margins. Agriculture, Ecosystems & Environment 326:107773. https://doi.org/10.1016/j.agee.2021.107773

Meeus I, Parmentier L, Pisman M, de Graaf DC, Smagghe G (2021) Reduced nest development of reared *Bombus terrestris* within apiary dense human-modified landscapes. Scientific Reports 11: 3755. https://doi.org/10.1038/s41598-021-82540-6

Meyer S, Unternährer D, Arlettaz R, Humbert J-Y, Menz MHM (2017) Promoting diverse communities of wild bees and hoverflies requires a landscape approach to managing meadows. Agriculture, Ecosystems & Environment 239:376-384. https://doi.org/10.1016/j.agee.2017.01.037

Montero-Castano A, Vila M (2012) Impact of landscape alteration and invasions on pollinators: a meta-analysis. Journal of Ecology 100:884-893. https://doi.org/10.1111/j.1365-2745.2012.01968.x

Nichols RN, Holland JM, Goulson D (2022a) A novel farmland wildflower seed mix attracts a greater abundance and richness of pollinating insects than standard mixes. Insect Conservation and Diversity 16: 190-204. https://doi.org/10.1111/icad.12624

Nichols RN, Wood TJ, Holland JM, Goulson D (2022b) Role of management in the long-term provision of floral resources on farmland. Agriculture, Ecosystems & Environment 335:108004. https://doi.org/10.1016/j.agee.2022.108004

Oksanen J et al. (2016) Community Ecology Package 'Vegan'. https://cran.r-project.org/web/packages/vegan/vegan.pdf

Parmentier L, Van Kerckvoorde A (2021) SWO: Pilootstudie ivm. de effecten van sinusbeheer op vegetatie en architecturale complexiteit in graslanden en de gevolgen naar voedselaanbod en biotoopwaarde voor pollinatoren - Addendum 1: vervolgstudie. Provincie West-Vlaanderen, Provincie Antwerpen, Provincie Vlaams-Brabant, Agentschap voor Natuur en Bos (ANB), Vlaamse Waterweg (VW), Oost- en West Vlaanderen

Peeters TMJ et al. (2012) De Nederlandse bijen (Hymenoptera: Apidae s.l.). - Natuur van Nederland, Leiden, The Netherlands

Potts SG, Woodcock BA, Roberts SPM, Tscheulin T, Pilgrim ES, Brown VK, Tallowin JR (2009) Enhancing pollinator biodiversity in intensive grasslands. Journal of Applied Ecology 46:369–379. https://doi.org/10.1111/j.1365-2664.2009.01609.x

Pywell RF, Warman EA, Sparks TH, Greatorex-Davies JN, Walker KJ, Meek WR, Carvell C, Petit S, Firbank LG (2004) Assessing habitat quality for butterflies on intensively managed arable farmland. Biological Conservation 118:313–325. https://doi.org/10.1016/j.biocon.2003.09.011

R Core Team (2021) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/ [Accessed February 1, 2023]

Saarinen K, Valtonen A, Jantunen J, Saarnio S (2005) Butterflies and diurnal moths along road verges: Does road type affect diversity and abundance? Biological Conservation 123:403-412. https://doi.org/10.1016/j.biocon.2004.12.012

Scheper J, Bommarco R, Holzschuh A, Potts SG, Riedinger V, Roberts SPM, Rundlöf M, Smith HG, Steffan-Dewenter I, Wickens JB, Wickens VJ, Kleijn D (2015) Local and landscape-level floral resources explain effects of wildflower strips on wild bees across four European countries. Journal of Applied Ecology 52:1165–1175. https://doi.org/10.1111/1365-2664.12479

Schweiger O, Maelfait JP, Van Wingerden W, Hendrickx F, Billeter R, Speelmans M, Augenstein I, Aukema B, Aviron S, Bailey D, Bukacek R, Burel F, Diekötter T, Dirksen J, Frenzel M, Herzog F, Liira J, Roubalova M, Bugter R (2005) Quantifying the impact of environmental factors on arthropod communities in agricultural landscapes across organizational levels and spatial scales. Journal of Applied Ecology 42:1129–1139. https://doi.org/10.1111/j.1365-2664.2005.01085.x

Senapathi D, Goddard MA, Kunin WE, Baldock KCR (2017) Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps.

Functional Ecology 31:26-37. https://doi.org/10.1111/1365-2435.12809

Steffan-Dewenter I, Tscharntke T (2000) Resource overlap and possible competition between honey bees and wild bees in central Europe. Oecologia 122:288-296. https://doi.org/10.1007/s004420050034

Stevens CJ, Dise NB, Mountford JO, Gowing DJ (2004) Impact of nitrogen deposition on the species richness of grasslands. Science 303:1876-1879. https://doi.org/10.1126/science.1094678

Stoate C, Boatman ND, Borralho RJ, Carvalho CR, de Snoo GR, Eden P (2001) Ecological impacts of arable intensification in Europe. Journal of Environmental Management 63:337–365. https://doi.org/10.1006/jema.2001.0473

Sugden EA, Thorp RW, Buchmann SL (1996) Honey bee native bee competition: Focal point for environmental change and apicultural response in Australia. Bee World 77:26-44. https://doi.org/10.1080/0005772X.1996.11099280

Tansley AG (1946) Introduction to plant ecology. George Allen & Unwin Ltd., London

Tölgyesi C, Vadász C, Kun R, Csathó AI, Bátori Z, Hábenczyus A, Erdős L, Török P (2022) Post-restoration grassland management overrides the effects of restoration methods in propagule-rich landscapes. Ecological Applications 32:e02463. https://doi.org/10.1002/eap.2463

Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C (2005) Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. Ecology Letters 8:857-874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Walther-Hellwig K, Frankl R (2000) Foraging distances of *Bombus muscorum*, *Bombus lapidarius*, and *Bombus terrestris* (Hymenoptera, Apidae). Journal of Insect Behavior 13:239-246. https://doi.org/10.1023/A:1007740315207

Westphal C, Bommarco R, Carré G, Lamborn E, Morison N, Petanidou T, Potts SG, Roberts SPM, Szentgyörgyi H, Tscheulin T, Vaissière BE, Woyciechowski M, Biesmeijer JC, Kunin WE, Settele J, Steffan-Dewenter I (2008) Measuring Bee Diversity in Different European Habitats and Biogeographical Regions. Ecological Monographs 78:653–671. https://doi.org/10.1890/07-1292.1

Westrich P (2018) Die Wildbienen Deutschlands. Eugen Ulmer, Stuttgart.

Woodcock BA et al. (2007) The potential of grass field margin management for enhancing beetle diversity in intensive livestock farms. Journal of Applied Ecology 44:60-69. https://doi.org/10.1111/j.1365-2664.2006.01258.x

Wynhoff I, van Gestel R, van Swaay C, van Langevelde F (2011) Not only the butterflies: managing ants on road verges to benefit *Phengaris* (Maculinea) butterflies. Journal of Insect Conservation 15:189-206. https://doi.org/10.1007/s10841-010-9337-8

Zhang YH, Loreau M, He NP, Zhang GM, Han XG (2017) Mowing exacerbates the loss of ecosystem stability under nitrogen enrichment in a temperate grassland. Functional Ecology 31:1637-1646. https://doi.org/10.1111/1365-2435.12850

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