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Supporting wild pollinators in agricultural landscapes through targeted legume mixtures

Lorna J. Cole^{a,*}, John A. Baddeley^b, Duncan Robertson^a, Cairistiona F.E. Topp^c,
Robin L. Walker^b, Christine A. Watson^b

^a Integrated Land Management, SRUC, Auchincruive Estate, Ayr KA6 5HW, UK

^b Rural Land Use, SRUC, Craibstone Estate, Aberdeen AB21 9YA, UK

^c Agriculture, Horticulture and Engineering Sciences, SRUC, West Mains Road, Edinburgh EH9 3JG, UK

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ABSTRACT

Insect-pollinated legumes are rich in plant-based proteins making them a vital constituent of sustainable healthy diets for people and livestock. Furthermore, they deliver or support a range of ecosystem services that underpin agricultural production and their prevalence in agricultural landscapes is likely to increase. Under typical implementation and management, the value of legumes to pollinators has, however, been questioned. Through exploring a range of legume crops, grown as monocultures and mixtures, this study aims to identify multi-functional legume cropping systems that optimise forage availability for a diversity of wild pollinators whilst delivering a wide range of agronomic and environmental benefits. This study innovatively explores legume mixtures concurrently with monocultures of the component species using replicated small-plot field trials established in two geographical locations. Observational plots assessed the richness and abundance of floral resources, and wild pollinators (i.e. bumblebees and hoverflies) throughout the peak flowering period. Densely flowering, highly profitable legumes (e.g. *Trifolium incarnatum* and *Trifolium* mixes) supported abundant and rich pollinator assemblages. The functional makeup of floral visitors was strongly influenced by flower structure and hoverflies, with their shorter proboscises, were largely constrained to legumes with shallower corolla and open weed species. Floral richness was not a key driver of pollinator assemblages; however, clear intra-specific differences were observed in flowering phenology. Combining functionally distinct legumes with respect to flower structure and phenology, will support a wider suite of pollinating insects and help stabilise the temporal availability of forage. For highly competitive legumes (e.g. *Vicia faba* and *Vicia sativa*), planting in discrete patches is recommended to reduce the risk of less competitive species failing in mixtures. Legumes can provide valuable forage for pollinators; however, they fail to meet all resource requirements. They should therefore be used in combination with agri-environmental measures targeted to promote early-season forage (e.g. hedgerows and farm woodlands), open flowers for hoverflies, saprophytic hoverfly larval resources (e.g. ditches and ponds) and nesting habitats (e.g. undisturbed field margins).

1. Introduction

Sustainably meeting future dietary requirements within our planetary boundaries remains a global challenge (Lassen et al., 2020; Willett et al., 2019). Insect pollination enhances yield and/or quality in 75% of the world's leading crops, accounting for an estimated 35% of food production (Klein et al., 2007). These insect pollinated crops include legumes, nuts and fruits which are particularly rich in proteins, lipids and micronutrients (e.g. Vitamin A and C, folic acid and carotenoids) vital to human wellbeing

(Eilers et al., 2011; Chaplin-Kramer et al., 2014). The maintenance of healthy pollinator assemblages is therefore critical in enabling us to sustainably meet future nutritional demands.

With the intensification of farming practices identified as a primary driver of insect pollinator declines (Potts et al., 2016), increasing food production whilst safeguarding pollination services presents a key challenge to agriculture. Despite negative relationships between intensive agriculture, pollinator populations (Potts et al., 2016; Kennedy et al., 2013), and pollination service delivery (Deguines et al., 2014);

* Corresponding author.

E-mail address: Lorna.Cole@sruc.ac.uk (L.J. Cole).

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agriculture can provide a key vehicle to conserve pollinators (e.g. via agri-environmental policy and marketing of environmentally friendly products) (Kovács-Hostyánszki et al., 2017). With approximately 40% of the EU under agricultural production (European Commission, 2018), it is difficult to perceive how we can adequately conserve pollinators without considering the agricultural matrix. Amongst the cocktail of drivers of declines (Potts et al., 2016), the loss of floral-rich habitats including hedgerows, species-rich grasslands and legume-rich leys is identified as an important contributory factor (Baude et al., 2016; Goulson et al., 2015). Indeed, agri-environmental interventions aimed at conserving insect pollinators typically focus on re-establishing floral resources (Winfree, 2010): for example, restoring species-rich grasslands, sowing field margins with nectar and pollen-rich mixes, and inclusion of flowering species such as legumes in rotations (Beyer et al., 2020; Scheper et al., 2015).

Dietary shifts towards more plant-based diets have a vital role to play in achieving food security (e.g. as outlined in the EAT-Lancet Commission healthy reference-diet: Willett et al., 2019), with plant-based proteins (i.e. nuts, seeds and legumes) providing an alternative to proteins derived from meat. Grain legumes (e.g. beans, peas and soybean) not only provide a rich source of protein for human consumption, but also for livestock feed, reducing the need for imported soybean in European countries (Watson et al., 2017). Furthermore, whether grown for grain (e.g. *Vicia faba*, *Pisum sativum*), forage (e.g. *Medicago sativa*, *Trifolium* spp.) or as a green manure (e.g. *Vicia sativa*, *Trifolium incarnatum*), legumes are particularly valuable due to their capacity to fix atmospheric nitrogen thus decreasing reliance on inorganic nitrogen (Everwand et al., 2017; Köpke and Nemecek, 2010; Watson et al., 2017). With legumes playing a critical role in enhancing the sustainability of our food production systems, their prevalence in future agricultural landscapes is likely to increase.

Fabaceae pollen is particularly protein-rich, and with pollen providing the proteins necessary for reproduction and larval development (Kleijn and Raemakers, 2008), legumes can provide a valuable source of forage for wild pollinators (Goulson et al., 2008; Hanley et al., 2008; Scheper et al., 2014). The loss of legume-rich habitats is implicated in wild bee declines, with bumblebee rarity linked to their specialisation towards collecting pollen from legumes, either because of tongue length (Goulson et al., 2008, 2005), or larval diet specialisation (Kleijn and Raemakers, 2008; Scheper et al., 2014). Pollinators and legumes show a strong interdependence, with legumes providing key forage whilst relying on insect pollination for reproduction/maintenance of genetic diversity (Suso et al., 2016). This interdependence is dependent on both plant (e.g. flowering period, nectar/pollen quality and quantity and flower shape which will influence accessibility) and pollinator traits (e.g. tongue length, activity period, nutritional requirements).

The value of legumes to pollinators has, however, been questioned due to the constrained flowering period of grain monocultures reducing the temporal availability of forage, frequency of grazing/cutting limiting flowering in forage legumes and their complex flower structures restricting accessibility of resources to pollinating taxa with short mouthparts (Cole et al., 2020; Hart et al., 2017; Underwood and Tucker, 2016). The legume species grown, alongside their management will influence the quantity/quality of pollen and nectar, timing and longevity of flowering, and accessibility of resources to different pollinating taxa. To inform policy, multifunctional legume cropping systems need to be identified that provide accessible and stable forage for a diversity of wild pollinators whilst retaining a wide range of agronomic and environmental benefits (e.g. reducing reliance on inorganic fertilisers, reducing the prevalence of weeds and diseases and improving soil health: Everwand et al., 2017; Kunz et al., 2016; Storkey et al., 2015; Watson et al., 2017).

Increasing the occurrence of legumes in intensive agricultural systems could provide an important mechanism to mitigate pollinator declines, however, success will depend on implementation and

management. This study innovatively explores legume mixtures concurrently with monocultures of the component species to better understand the interactions between legumes and wild pollinators. Increasing our understanding of the timing, availability, and accessibility of floral resources in legumes will help to identify legume cropping systems that provide a stable source of forage for a diversity of pollinators. Through monitoring wild pollinators, specifically bees (Hymenoptera: Apiformes) and hoverflies (Diptera: Syrphidae), on replicated small plot trials we test the following predictions:

- 1) Legume species differ in the quality and availability of floral resources, and that the accessibility of these resources differs between pollinator functional groups (e.g. long tongued bumblebees, hoverflies with short proboscises).
- 2) Legume species differ with respect to the timing and duration of flowering impacting on how wild pollinators utilise different species throughout the season.
- 3) When compared to monocultures legume mixtures support richer pollinator communities and have more prolonged flowering periods due to interspecific differences in flowering phenology.

2. Materials and methods

2.1. Experimental design

Small plot field trials were established in 2016 and 2018 at two geographical regions, Midlothian (55°52'33.1"N 3°12'18.3"W) and Aberdeenshire (2016: 57°21'13.0"N 2°23'13.9"W and 2018: 57°17'57.8"N 2°03'47.0"W), Scotland UK (plot size: Midlothian 4 m x 6 m, Aberdeenshire 4 m x 10 m). A total of 15 legume treatments were established at each site; with this study focussing on 11 treatments present in both study years. The selected treatments included seven legume monocultures, and three mixtures each containing three legume species (Table 1). While resource constraints did not permit a full factorial design, legume mixtures were targeted to reflect differences in taxonomic diversity (e.g. *Trifolium* spp. mix versus *Trifolium pratense*/*Medicago lupulina*/*Medicago sativa* mix) and structural diversity (e.g. *T. pratense*/*M. lupulina*/*M. sativa* mix with low structural diversity versus *Vicia faba*/*Trifolium repens*/*Vicia sativa* mix with high structural

Table 1

List of fixed effects included in the modelling process. For each legume treatment variety and sowing rate are provided in brackets.

Fixed effect	Description
Legume treatment	
Monocultures	Field Beans <i>Vicia faba</i> (Fuego; 200 kg ha ⁻¹) Vetch <i>Vicia sativa</i> (Jose 2016; Early English 2018: 60 kg ha ⁻¹) Lucerne <i>Medicago sativa</i> (Neptune 2016; Marshall 2018: 20 kg ha ⁻¹) Black Medic <i>Medicago lupulina</i> (Virgo pajbjerg; 10 kg ha ⁻¹) Crimson Clover <i>Trifolium incarnatum</i> (Pier 2016; Heusers Ostsaat 2018: 10 kg ha ⁻¹) White Clover <i>Trifolium repens</i> (Aberpearl; 7 kg ha ⁻¹) Red Clover <i>Trifolium pratense</i> (Merula; 10 kg ha ⁻¹)
Mixtures	<i>Trifolium pratense</i> (0.33 kg ha ⁻¹) / <i>Medicago lupulina</i> (0.33 kg ha ⁻¹) / <i>Medicago sativa</i> (0.66 kg ha ⁻¹) <i>Trifolium pratense</i> Clover (0.33 kg ha ⁻¹) / <i>Trifolium repens</i> (0.23 kg ha ⁻¹) / <i>Trifolium incarnatum</i> (0.33 kg ha ⁻¹) <i>Trifolium repens</i> (0.23 kg ha ⁻¹) / <i>Vicia sativa</i> (20 kg ha ⁻¹) / <i>Vicia faba</i> (66.7 kg ha ⁻¹)
Floral density	Area of 2 × 1 m quadrat with flowers actively flowering (averaged over sampling dates in each year)
Floral richness	Number of plant species in flower (averaged over sampling dates in each year)
Year	Two survey years (i.e. 2016, 2018)
Region	Geographical Region (i.e., Midlothian, Aberdeenshire)
Month	Sampling period (i.e., Mid-July, Early August, Mid-August, September)

diversity). To allow direct comparison between species grown as monocultures and mixtures, all species included in mixtures were also grown as monocultures. Trials were established in a randomised block design with the eleven legume treatments replicated across three blocks (i.e. 33 plots per geographical region per year). Legume crops were sown in April of each year (seed depth 2–4 cm) with *M. sativa* seed sown with inoculum at a rate of 10 g per kg of seed.

2.2. Pollinator and floral resource monitoring

For each plot and sampling date, pollinator observational quadrats (1 m x 2 m) were established in an area that typified the plant species in flower at that time. Care was taken to avoid plot edges, and to ensure that both planted and weed species actively flowering were captured. All actively flowering plants in the quadrat were identified to species level and quantified using the Domin scale, converted to percentage cover prior to statistical analyses (Currall, 1987).

Pollinator observational quadrats were monitored for 8 minutes taking care not to shade the quadrat. All actively foraging bumblebees and hoverflies (i.e. observed probing for nectar for at least two seconds) were identified to species level and quantified. Specimens that could not be identified in the field were caught and brought back to the laboratory for identification following Stubbs and Falk (2012) for hoverflies and Falk (2015) for bees. To minimise disturbance, bumblebees that are not readily identified by morphological features (i.e. *Bombus lucorum*, *Bombus cryptarum*, *Bombus magnus* and *Bombus terrestris*) were aggregated to a single group (i.e. *Bombus terrestris* agg.) (Wolf et al., 2010). To reduce errors associated with double counting, pollinators observed leaving the quadrat and foraging within 50 cm were not counted as new pollinators if they returned to the quadrat. When a pollinator was observed visiting multiple flower species, only the first flower species the pollinator visited was recorded.

All observations were conducted between 10.00 and 16.45 h under conditions deemed suitable for recording pollinators, specifically temperature 13–17 °C with at least 60% clear sky, or over 17 °C and not raining and with a maximum wind speed of 4 on the Beaufort Scale (Cole et al., 2017). With the exception of Aberdeenshire in 2016, where sampling did not commence until August, sampling was conducted at 2–3 week intervals, from Mid-July until September giving four survey periods (Mid-July; Early August, Mid-August and Early September). All plots were surveyed once during each survey period with survey periods chosen to span the flowering phenology of the legume species present.

2.3. Data analyses

To visually explore temporal trends in the frequency of interactions between pollinators and flowers, the total abundance of each pollinator species visiting a specific plant species was calculated for each sampling period (irrespective of geographical region, legume treatment and year). Heatmaps were then created from this summarised data. Heatmaps were also created to visualise the relationship between pollinator and plant functional traits. Pollinators were classified by taxa (i.e. hoverflies/bumblebees) and tongue/proboscis length (Table S1: Gilbert, 1981; Gilbert et al., 1985; Goulson et al., 2005). Weeds were grouped into complex (e.g. *Galeopsis tetrahit* L.) or simple flower structures (e.g. *Tripleurospermum inodorum* (L.)) based on Baude et al. (2016) (Table S2). For each functional group (e.g. short-tongued bumblebees), the relative abundance observed foraging on specific legume species, complex weed species and simple weed species was calculated and visualised via a Heatmap.

2.4. Modelling community structure

For each survey date and plot, two measures of community structure were calculated for plants in flower, bumblebees and hoverflies:

- Abundance/floral density: Percentage area of the 2 × 1 m quadrat with plants actively flowering, number of bumblebees/hoverflies observed foraging
- Species richness: Number of species recorded in each taxa

For floral resource variables, models were fitted to the above measures of community structure. Pollinators, particularly bees, however, were rarely observed foraging in a plot when legumes were not in flower. It was therefore not possible to explore effects of survey period, and indeed interactions between survey period and other fixed effects. Consequently, pollinator measures of community structure were first averaged over survey periods in a particular year and analyses were performed on the resultant averages (i.e. n = 12; 3 plots x 2 geographical regions x 2 survey years). Due to sparsity of data, certain treatments were removed (i.e. where no pollinators were observed foraging in a specific treatment, in a specific region, in a specific year) prior to analyses. For hoverflies *V. faba* plots in Aberdeenshire, 2018 were excluded (resultant n = 9). For bumblebees *T. repens* plots in Aberdeenshire, 2016 were removed (resultant n = 9) and for the treatment *M. lupulina* only Midlothian plots in 2016 yielded sufficient data for analyses (resultant n = 3).

For all response variables, the following fixed effects, and their interactions, were considered: year, region and legume treatment (Table 1). Additionally, for bumblebee and hoverfly response variables, floral density and floral richness were also explored as covariates to try and determine if differences in legume treatments were primarily driven simply by flower abundance and richness measures. For floral response variables, month and associated interactions were explored.

For floral density, and all bumblebee and hoverfly response variables (i.e. where response variables were based on averages), Linear Mixed Models (LMMs) were fitted using Residual Maximum Likelihood (REML). Data were log transformed (or, in the case of bumblebee abundance, square-root transformed) to normalise where required. For floral richness (i.e. the count of flower species observed in a specific quadrat on a specific date), Generalised Linear Mixed Models (GLMMs) were fitted assuming Poisson distributed errors.

To account for geographical and temporal variation and permit a greater strength of comparison between treatments within a block, each block was given a unique identifier and included as a random effect (i.e. total of 12 blocks corresponding to three blocks per region per year). For models where floral area was the response variable, this unique identifier also included month.

Models were fitted using a structured, forward stepwise selection process involving three steps (Fig. S1). At each step, models in the confidence set were identified by Akaike's Information Criterion corrected for small sample sizes (i.e. $\Delta AIC_c < 2$) and these models were selected for the next step (Burnham and Anderson, 2002). For GLMMs statistical significance of fixed effects were estimated from model comparison using the Likelihood Ratio Test.

All analyses were conducted in R version 3.5.2 (R Core Team, 2018) and all models were fitting using the lme4 package (Bates et al., 2015). Diagnostic plots (i.e. residuals against fitted values and QQ plots), were examined to validate homoscedasticity and normality of residuals (validated with Shapiro-Wilk test) with no major departures from equality of variance and normality detected.

3. Results

3.1. Overview

A total of six species of bumblebee (495 individuals) and 27 species of hoverfly (548 individuals) were recorded over the duration of the experiment (Table S1).

3.2. Impact of season and legume treatment on plant-pollinator interactions

Clear temporal differences were observed in the flowers that pollinators visited, reflecting differences in flowering period and resource value (i.e. nectar and/or pollen) (Fig. 1). The number of plant-pollinator interactions observed was lowest in July, when few legumes were flowering. In July, hoverflies predominantly foraged on weed species (i.e. 86% of interactions), whereas, bumblebees were observed on both *V. faba* (i.e. 46%) which were in full flower and *T. incarnatum* (i.e. 54%) which had just commenced flowering. Plant-pollinator interactions

peaked in August when *T. incarnatum* attracted the highest proportion of foraging bumblebees (i.e. 64%) and hoverflies (i.e. 27%). Comparatively few pollinators were observed on *V. sativa* and *M. sativa*, despite flowering being well established. In September, *T. incarnatum* began to senesce and visitations to this plant started to decline. The frequency that bumblebees were observed foraging on *T. pratense*, increased, coinciding with flowering commencing in this species.

A heatmap, based on pollinator functional groups, indicated the importance of *T. incarnatum* for all pollinators, irrespective of tongue length (Fig. 2). *Medicago sativa* was frequently visited by hoverflies, and despite flowering late in the season, *T. pratense* was one of the most

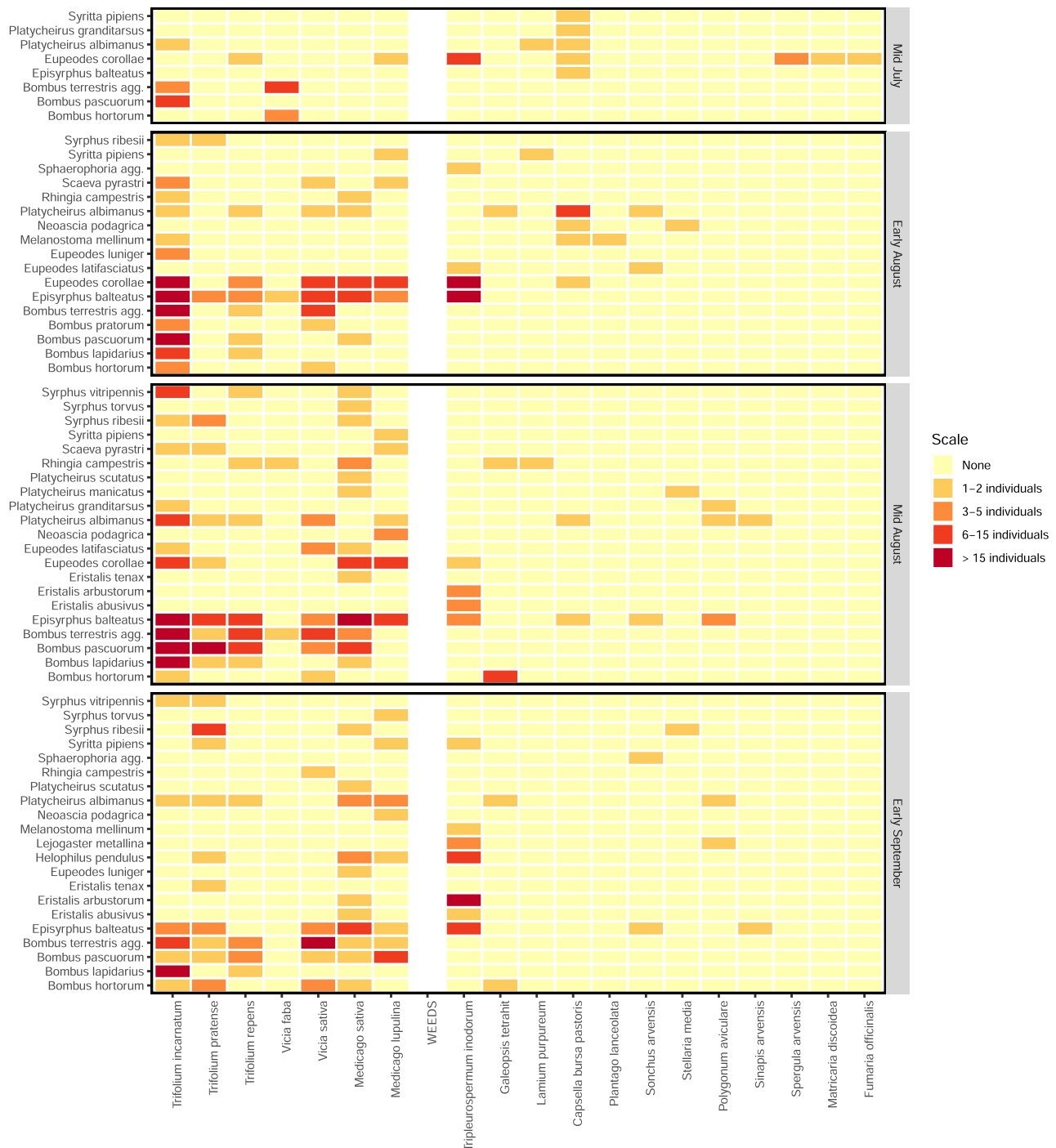


Fig. 1. Heatmap illustrating temporal trends in the interaction frequency between pollinator and plant species. Data is summarised irrespective of geographical location and year. To ease interpretation pollinators observed only once during the study are omitted as are plant species where only one interaction was observed.

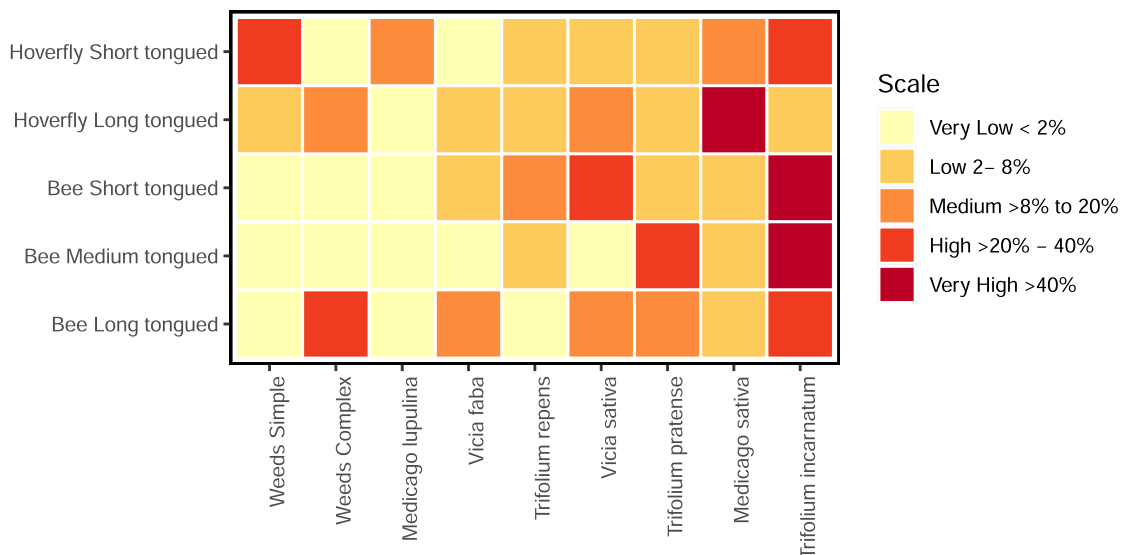


Fig. 2. Heatmap illustrating the relative abundance of each pollinator functional group observed foraging on simple and complex weeds and the seven legume species. Graphs are based on percentage data summarised for each legume treatment irrespective of year, region, and month.

visited legumes for both medium and long-tongued bumblebee species. Although, *V. faba* and *V. sativa* were frequently visited by both short and long-tongued bumblebees, shorter-tongued species were primarily observed nectar-robbing. With the exception of short-tongued hoverflies foraging on open weeds species (e.g. *Capsella bursa-pastoris* (L.), *Tripleurospermum inodorum* (L.)), pollinators showed a clear preference for legumes.

3.3. Impact of legume treatment on floral resources

Two models were included in the confidence set for floral density and five models were included for floral richness (Table 2, Table S3; Table S4). For floral abundance, the most parsimonious model included year, region, month, legume treatment and the interaction between month and treatment. Floral density tended to be higher in Aberdeenshire (27.5 ± 2.22 SE area) than Midlothian (17.1 ± 1.47 SE area). For floral richness, the most parsimonious model included month, region, and treatment; however, only treatment was significant.

Both floral density and richness significantly differed between legume treatments and these effects appeared consistent across regions and years (Fig. 3). Floral density was highest in *T. incarnatum* and

Trifolium mix (consisting of *T. repens*, *T. pratense* and *T. incarnatum*) plots and lowest in *V. sativa* plots. While it may be expected that mixtures would support a higher number of flowering species, this was dependant on the mixture. The clover mix and the *T. pratense*/*M. lupulina*/*M. sativa* mix supported the highest number of flowering plant species, the *V. faba*/*V. sativa*/*T. repens* mix, however, was one of the most floristically impoverished treatments. Indeed, *M. lupulina* and *T. repens* monocultures supported higher flowering plant richness than this mixture as a result of a comparatively high number of weed species in these plots.

For floral density, a significant interaction was detected between month and treatment highlighting legume treatments differed in flowering phenology (Fig. 4). *Vicia faba* was the only legume with peak flowering in July and flowering quickly senesced in early August. Flowering in *T. incarnatum* was particularly prolific in mid to late-August. Flowering in *T. repens*, *M. sativa* and *M. lupulina* was not well established until mid-August and persisted into September. *Trifolium pratense* was the last legume to flower, with peak flowering occurring in September. The decline in flowering in *T. incarnatum* monocultures in September was somewhat stabilised in the *Trifolium* mix due to an increase in the later flowering *T. pratense*. The July flowering peak was

Table 2

Results derived from LMMS (GLMMs for Floral Richness) based on the best supported models (i.e., AICc < 2; Supplementary Table 1) for each response variable. The direction of significant effects for Floral Density were positive. For consistency across models F-values are provided, however, Flower Richness was fitted using a GLMM and thus probability values are derived from model comparison using the Likelihood Ratio Test. Numerator and ranges for denominator degrees of freedom (which vary in mixed models for different response measures as they are based on estimated variance components) are also provided. Shading indicates fixed effects were not tested for a specific response variable. NS denotes that a specific fixed effect was included in confidence set but not found to be significant. Fixed effect parameter estimates are provided in Table S4 for flowers and S5 for pollinators.

Taxa	Measure of community structure	Year (1, 11–93)	Month (3, 36–37)	Region (1, 10–37)	Legume treatment (9, 84–108)	Floral density (1, 73–93)	Month * Legume treatment (9, 108)	Region * Month (3, 18)
Flower	Abundance	5.16*	14.86***	5.18*	31.46***		16.80***	
	Abundance		12.32***	6.97*	31.46***		16.80***	
	Richness		NS	NS	7.19***			
	Richness		NS		7.19***			
	Richness			NS	7.19***			
	Richness			NS	7.19***			NS
Bumblebee	Abundance	12.31***			2.77**	43.42***		
	Richness	13.05***			2.97**	37.67***		
Hoverfly	Abundance			9.19*	10.57***			
	Richness			7.93*	8.50***			
	Richness				8.57***			

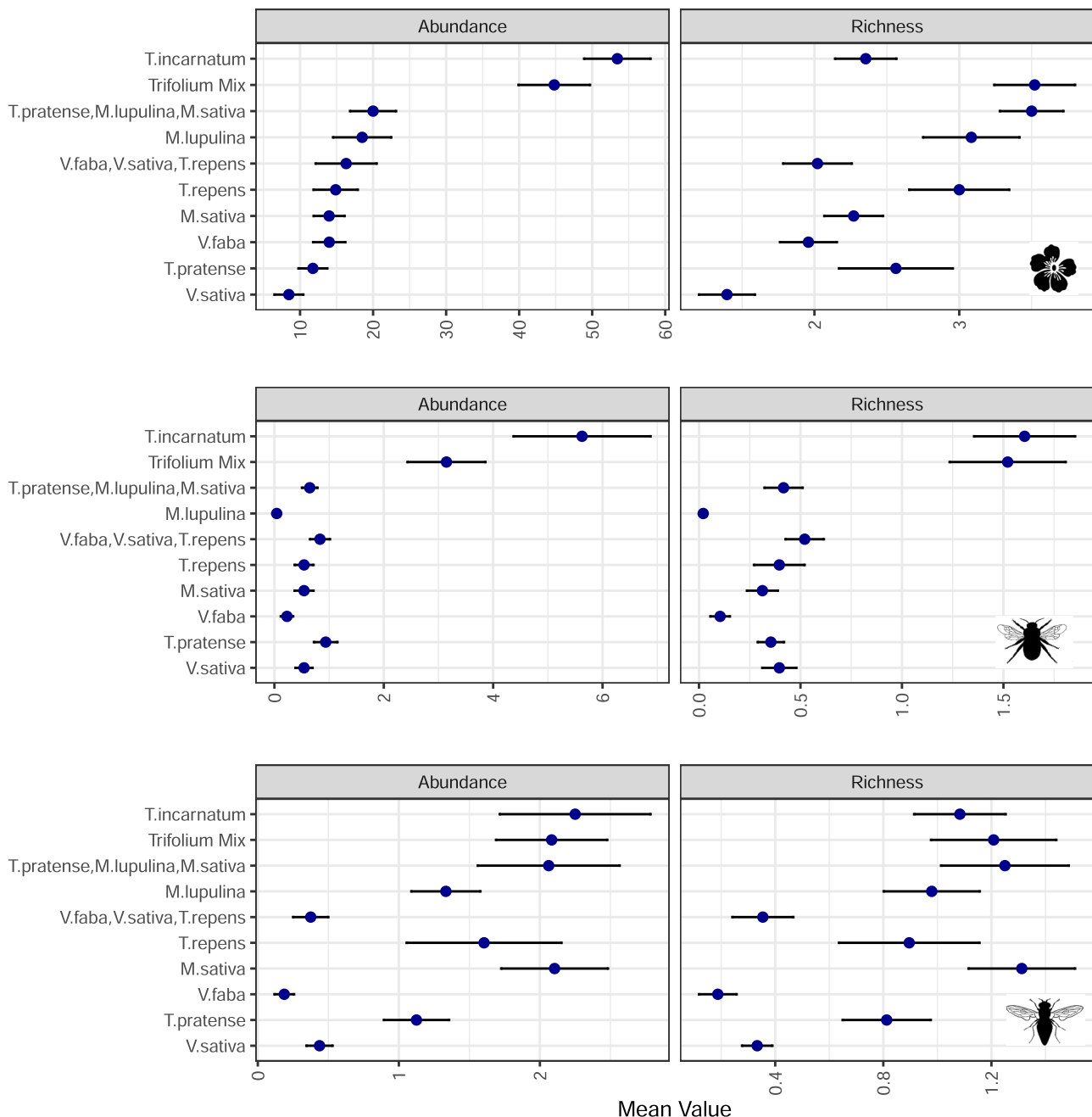


Fig. 3. Impact of legume treatment on abundance and richness for flowers (top), bumblebees (middle) and hoverflies (bottom). Graphs are based on the raw data. For each taxa, first the mean value per plot per year (i.e. averaging over survey periods) was calculated. Then for each treatment the mean value (\pm SEM) was calculated, irrespective of region and year. Fixed effect parameter estimates are provided in [Table S4](#) for flowers and [S5](#) for pollinators.

more evident in *V. faba* monocultures than in the *V. faba*, *V. sativa* and *T. repens* mixture, however, the presence of *V. sativa* in the mixture prolonged flowering until September, indicating that *V. faba* and *V. sativa* complemented each other in flowering period. Worth noting, in this mixture *T. repens* was outcompeted and rarely flowered, limiting its value to pollinators in these study plots.

3.4. Impact of legume treatment and floral resource on pollinators

Bumblebee abundance and richness identified one model in the confidence set indicating that year, legume treatment and floral density were significant ([Table 2](#); [Table S3](#); [Table S5](#)). There was, no evidence that bumblebees were influenced by floral richness (i.e. Δ AICc ≥ 2 in models including floral richness), and mixtures didn't consistently

attract more bumblebees than monocultures. The abundance and richness of foraging bumblebees did, however, increase with floral density ([Table 2](#)).

Treatment effects appeared consistent across regions and years (i.e. no significant interaction between legume treatment and year/region was detected). Legume treatments containing *T. incarnatum*, either grown as a monoculture or incorporated in a *Trifolium* mix, supported the highest richness and density of bumblebees with approximately six times more bumblebees recorded in *T. incarnatum* treatments than *T. pratense* (the next best performing treatment with respect to bumblebee abundance) ([Fig. 3](#)). These treatments also supported the highest floral density, although treatment effects could not solely be attributed to differences in floral density. Bumblebee richness and abundance was lowest in *V. faba* and *M. lupulina* treatments.

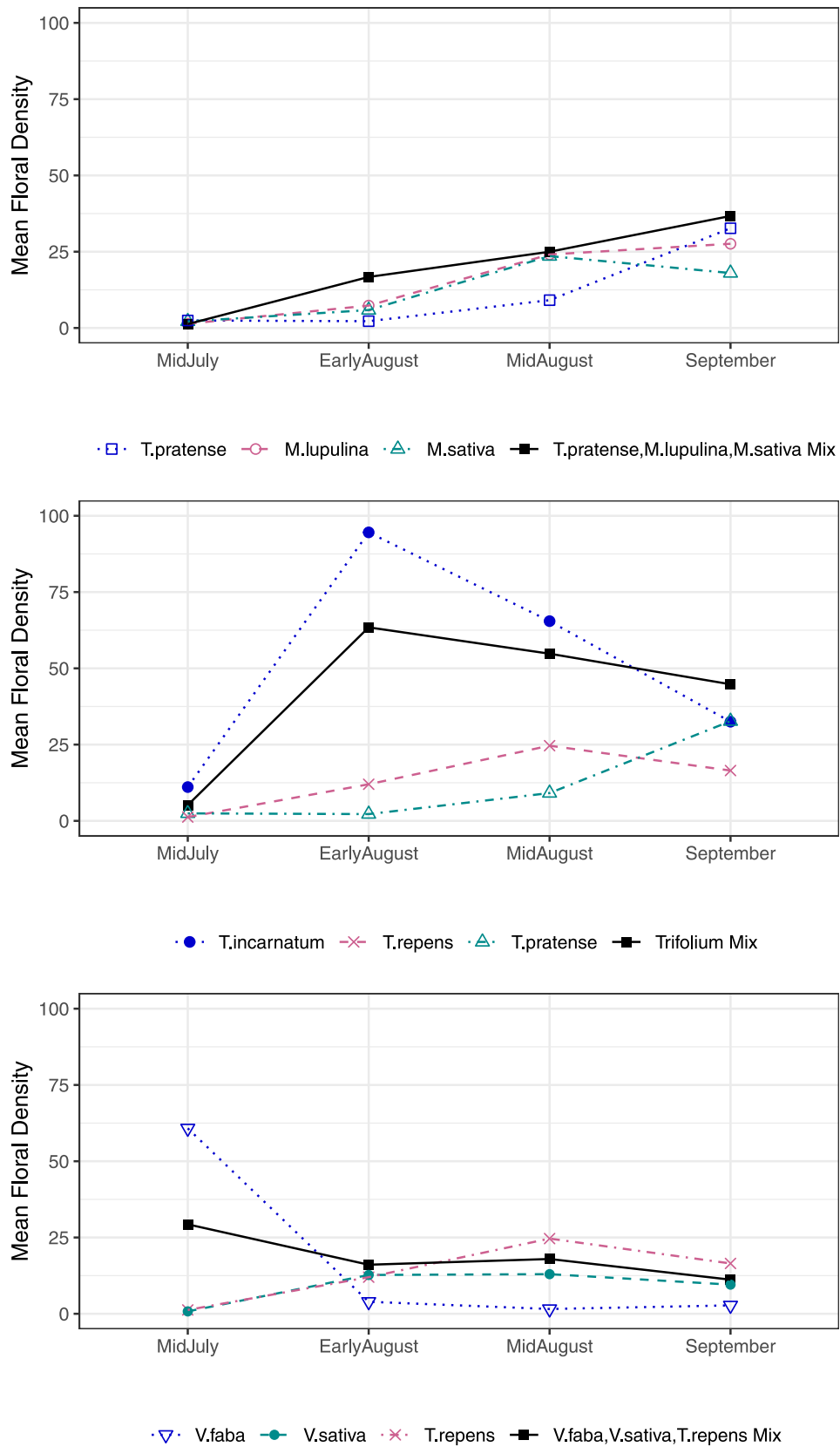


Fig. 4. Impact of season on mean floral density, irrespective of region and year. Each plot shows the mean floral abundance for a specific mixture (solid line), alongside floral abundance in legume monocultures present in the mixture in question (broken lines). This enables direct comparison between flowering phenology when species are planted as a mixture versus a monoculture.

For hoverfly abundance and richness, the most parsimonious models contained the fixed effects region and legume treatment (Table 2; Table S3; Table S5), with both response variables higher in Aberdeenshire (Abundance = 1.92 ± 0.22 SEM, Richness = 1.09 ± 0.11 SEM) than Midlothian (Abundance = 0.79 ± 0.09 SEM, Richness = 0.59 ± 0.06 SEM). There was no detectable improvement when year was included as a predictor, indicating consistency in hoverfly populations across survey years. Including floral abundance and richness as fixed effects again found no clear improvement to model fit (i.e. $\Delta AICc > 2$).

As with bumblebees, legume treatment strongly influenced hoverflies and effects appeared consistent across survey years and regions. Legume treatments that contained *T. incarnatum* (either as a monoculture or a mixture) were again amongst the best performing treatments (Fig. 3). However, for hoverflies, other treatments performed to a similar extent. The *M. sativa*, *M. lupulina* and *T. pratense* mix and *M. sativa* monoculture performed well, supporting a high number of hoverflies and hoverfly species. This indicates that although *M. sativa* supported few foraging bumblebees, it was relatively good for hoverflies.

4. Discussion

Grain and forage legumes have a clear role to play in increasing the sustainability of our food production systems, and consequently they are likely to become more widespread in our countryside. High densities of pollinators were observed foraging on resource-rich legumes, indicating that carefully targeted initiatives that focus on increasing such species could help conserve pollinators in intensive agricultural landscapes (e.g. legume-rich grasslands, nectar/pollen-rich legume supported cropping systems). Hoverflies and bumblebees were primarily driven by flower structure, resources offered, flowering period and floral density. Due to differences in flowering phenology, certain legume species (e.g. *T. incarnatum* and *T. pratense*) complement each other in their flowering periods indicating targeted mixtures could stabilise forage over the season.

4.1. Impact of legume treatment on floral resources

The abundance and richness of floral resources were strongly influenced by legume treatment and inter-specific differences were found in flowering phenology. Richness of floral resources was not simply related to the number of species sown but was instead dependant on intra-specific competition between both sown and weed species (Hicks et al., 2016; Wassmuth et al., 2009). Plant functional traits played a critical role in interactions between plant species with traits such as seed size, maturation rate and seedling vigour driving differences in competitive ability (Place et al., 2011; Uchino et al., 2011). *Vicia sativa* and *V. faba*, with their relatively heavy seeds, were highly competitive and quickly established a dense canopy that prevented other species from flowering resulting in a relatively low species richness. *Trifolium repens* and *M. lupulina* on the other hand, with their smaller seeds were slower to establish, lower-lying, and when grown as monocultures supported a relatively high number of flowering weeds. While there was strong evidence of competitive interactions, there was no clear evidence of facilitative interactions: i.e. whereby flowering was enhanced when species were grown as mixtures when compared to monocultures (Justes et al., 2021).

4.2. Impact of legume treatment on pollinator assemblages

A variety of factors influenced the value of legume treatments including when and how prolifically they flower (Ebeling et al., 2008), flower structure impacting on the accessibility of resources (Fontaine et al., 2006), and the value of the floral rewards (Baude et al., 2016; Blüthgen and Klein, 2011; Filipiak, 2019; Mayer et al., 2012). Contrary to previous research (Cole et al., 2017; Ebeling et al., 2008; Meyer et al.,

2009), pollinator diversity was not related to floral richness. With plant species richness constrained to a relatively low number of functionally similar species, the stronger impact of legume treatment may be expected. The availability of nectar and pollen is strongly linked to floral abundance (Hicks et al., 2016), and the most prolific flowering treatments (i.e. *T. incarnatum* and *Trifolium* mix) supported high densities of both bumblebees and hoverflies. The prevalence of bumblebees foraging on *T. incarnatum* in July, despite *V. faba* flowering more prolifically, indicates that crimson clover also provided high-quality resources. In contrast to bumblebees, hoverflies were not influenced by floral density which is probably due to floral density being driven by flowering in legumes which are less accessible to hoverflies (Fontaine et al., 2006; Rijn and Wäckers, 2016).

The functional makeup of floral visitors was strongly influenced by tongue/proboscis length. Fabaceae with complex flower structures (e.g. *V. faba* and *V. sativa*) were inaccessible to taxa with shorter mouthparts (e.g. many hoverfly species), while shorter-tongued bumblebees (e.g. *Bombus terrestris* agg.) typically nectar-robbed (Beyer et al., 2020; Garratt et al., 2014). Hoverflies with short proboscises preferred legumes with shallower corolla and simpler flower structures (e.g. *M. sativa*, *M. lupulina*) (Kovács-Hostyánszki et al., 2016) and open accessible weed species (e.g. scentless mayweed *T. inodorum*) (Rijn and Wäckers, 2016). Indeed, 33% of all hoverfly interactions occurred on weeds, and the prevalence of weeds in *M. lupulina* and *T. repens* plots resulted in comparatively high densities of hoverflies. The role of hoverflies in providing pollination (Rader et al., 2016) and pest regulating (Jauker et al., 2009; Mayer et al., 2012) services is becoming increasingly recognised. With hoverflies having limited accessibility to some legumes, care should be taken to design mixtures which include flowers with open structures (e.g. Asteraceae and Apiaceae) or legume species with shorter corolla (e.g. *M. lupulina* or *M. sativa*).

4.3. Temporal stability of resources

Although there was no obvious distinction in the floral abundance or richness of mixtures versus monocultures, clear intra-specific differences were observed in flowering phenology which drove seasonal changes in the flowers that pollinators visited (Carvell et al., 2011; Cole et al., 2017; Ebeling et al., 2011). Flowering in most legumes peaked in August, with *V. faba* flowering earlier (i.e. July) and *T. pratense* flowering later (i.e. September). With gaps in forage limiting pollinator populations, stabilising floral resources throughout the season is crucial (Scheper et al., 2015; Timberlake et al., 2019). *Vicia faba* and *T. pratense* provide a pulse of food when alternative forage is lacking and have been shown to positively impact on bumblebee populations (Beyer et al., 2020; Rundlöf et al., 2014). Carefully targeting legume mixtures to include species that flower in early-summer (e.g. *V. faba*), mid-summer (e.g. *T. incarnatum* and *V. sativa*) and late-summer/autumn (e.g. *T. pratense* and *M. sativa*) will therefore help to stabilise floral resources (Carvell et al., 2011). Indeed, in the current study, pollinators were observed to switched from *T. incarnatum* to *T. pratense* as the former senesced and the latter started to flower. However, even such targeted mixtures would fail to deliver early-season resources in North-West Europe (April to June: Cole et al., 2020).

4.4. Management implications

The restricted flowering period of grain legumes, and frequency of cutting/grazing in forage legumes typically limits their potential to provide forage for pollinators (Underwood and Tucker, 2016). Adopting more pollinator-friendly management, through reduction of pesticides, selecting a diversity of resource-rich species/cultivars, and sympathetic grazing/cutting regimes (e.g. in forage legumes alternative grazing management such as tall grass grazing can facilitate flowering) will increase their value (Cole et al., 2020; Kovács-Hostyánszki et al., 2016; Storkey et al., 2015; Underwood and Tucker, 2016).

With legume species differing in flower structure and flowering phenology, selecting mixtures that exploit these differences will increase their value to insect pollinators (Blüthgen and Klein, 2011). For example, including *T. incarnatum* alongside more economically viable species (e.g. *V. faba*) could enhance accessibility and stabilise forage thus supporting a wider suite of pollinators for a longer period of time. Combining functionally different legume species will not only enhance pollination services but also increase the wider environmental benefits (Storkey et al., 2015). Our research, however, highlights that interspecific competition influences the ability of some legumes to persist and flower in mixtures, with competitive species (e.g. *V. faba* and *V. sativa*) outcompeting less competitive legumes. Competitive species should therefore be included in legume mixtures with caution and when including such species consideration should be given to planting in discrete patches of monocultures instead.

Even mixtures of functionally distinct legume species will still fail to provide all resources pollinators require, with early season forage, hoverfly larvae resources and nesting sites lacking (Cole et al., 2020; Scheper et al., 2013). Legume crops should therefore be considered alongside the promotion of habitats known to be rich in early season resources (e.g. flowering hedgerows/trees: Baude et al., 2016), hoverfly resources (e.g. open flowers for accessible forage alongside ditches and ponds to provide habitat for saprophytic larvae) and suitable nesting habitats (e.g. tussocky field margins). Legumes are likely to play an integral role in future farming systems and this research highlights that if implemented sensitively they could help to mitigate pollinator declines (see supplementary material for a policy briefing outlining key actions: SPolicyBrief). To promote the interdependence between pollinators and legume species, agricultural systems should optimise the functional diversity of legume cropping systems in addition to supporting agri-environmental habitats rich in complementary resources.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2021.107648.

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