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RESEARCH ARTICLE

Flower strip effectiveness for pollinating insects in agricultural landscapes depends on established contrast in habitat quality: A meta-analysis

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Abstract

1. Flower strips have become a prevalent measure in agricultural landscapes to counteract biodiversity loss and especially promote pollinators. Although their benefits for pollinating insects have been frequently evaluated and reported, generalized conclusions about optimal settings for effective flower strips are still difficult. From the perspective of pollinators, flower strips vary distinctly in habitat quality, and the same applies for the control sites selected for scientific studies.
2. In this study, we used a meta-analytic approach based on a systematic review of recent studies (2009–2020) to analyze the relationship between flower strip effectiveness for pollinators and the contrast in habitat quality between flower strips and control sites. We extracted 350 data entries from 29 of 172 studies based on available data for richness or abundance of the pollinator taxa groups Apiformes, Lepidoptera and Syrphidae as response variables, for both flower strips and control treatments. All flower strips and control treatments were assigned a habitat quality score including information on spatial dimension, floral resources and management. Moreover, we included information on landscape complexity as measured by percent cover of seminatural habitats in the studied landscape.
3. In general, our results of meta-analytical models showed an increasing effect size of flower strips on pollinators for higher contrasts in habitat quality between flower strips and control treatments. This relationship was consistent across pollinator taxa and different levels of landscape complexity. Altogether, in terms of pollinator habitat quality, high-quality flower strips were more attractive than low-quality flower strips, and the reported effectiveness of flower strips decreased from low-quality to high-quality control treatments.
4. We recommend that results of future studies evaluating flower strips for pollinators are always linked with the contrast in habitat quality between selected flower strips and control treatments.

KEYWORDS
agri-environmental measures, bees, butterflies, ecological contrast, hoverflies, landscape context

1 | INTRODUCTION

Biodiversity loss has become a major concern in agricultural landscapes throughout Europe in the last decades (Cardinale et al., 2012; Díaz et al., 2019; Dirzo et al., 2014; Mupepele et al., 2021; Ortiz et al., 2021). In the face of this decline, the Common Agricultural Policy (CAP) of the European Union (EU) has promoted incentive measures for environment-friendly management as a practical solution to mitigate or reverse the negative impact of agriculture intensification on biodiversity (Pe'er et al., 2019, 2022). Designed as Agri-Environment Schemes (AES), such measures are financially subsidized by the CAP to compensate farmers for loss of income associated with introducing less intensive management and targeted activities promoting farmland biodiversity (Batáry et al., 2015). Currently, a great variety of AES promoting restoration, management or creation of different biodiversity-friendly habitats exists in the 27 member states of the EU, United Kingdom, Switzerland and Norway (Ekroos et al., 2014).

Among current AES, areas sown with seed mixtures of wild flower species have become a prevalent scheme to counteract loss of biodiversity and promote related ecosystem services in agricultural landscapes (Haaland et al., 2011; Uyttenbroeck et al., 2016). Such areas, commonly known as wildflower areas, sown flower margins, wildflower strips or simply (and hereafter) flower strips, provide food resources, shelter and overwintering habitat for different animal taxa. They are especially known to attract flower-visiting insects benefiting both local abundance and species richness (Carvell et al., 2007; McHugh et al., 2022; Scheper et al., 2015; Williams et al., 2015). Since their implementation as AES, flower strips have been realized quite differently across Europe (Haaland et al., 2011; Kowalska et al., 2022). Their spatial dimension, plant species composition and management depend on regional goals and country-specific regulations. For example, the dimension of flower strips is usually ruled by spatial and local-specific needs within the regional agricultural context, being established as crop margins/boundaries of low area but large extension or as set-aside areas/patches of variable size (Haaland et al., 2011). Similarly, strips are usually sown with seed mixtures of wild flowers alone or in combination with grass seeds, or mixtures directed to benefit specific taxa (i.e. bees and bumblebees, so-called pollen & nectar mixture). Together with the effects of site conditions, such as soil texture or sun exposure, and management on the establishment and development of flower strips, this leads to high variability in plant species composition among sites (Gardarin & Valantin-Morison, 2022; Nichols et al., 2022; Schmidt et al., 2022). Due to the variability on flower strips' properties and implementations across Europe, such studies may provide incomplete information regarding their general effectiveness in agricultural landscapes.

There is an important bulk of literature supporting the positive effects of flower strips on pollinator species richness and abundance, and its effectiveness as AES has been assessed and reported frequently in the last decade (Haaland et al., 2011; Lowe et al., 2021; Scheper et al., 2013; Zamorano et al., 2020). However, a comparison of studies evaluating the effectiveness of flower strips as AES for pollinators can be critical: First, flower strips have been studied using various types of control sites, from unmanaged field margins to crop fields (e.g. Lowe et al., 2021). Second, those studies were based on different seed mixtures, different spatio-temporal scales and different landscape contexts. Several studies suggest that the landscape heterogeneity or complexity is of major importance for the establishment and survival of pollinator communities in agricultural landscapes (Bergholz et al., 2022; Fijen et al., 2019; Kennedy et al., 2013; Senapathi et al., 2017). Therefore, studies on the effectiveness of flower strips often differentiate between simple and complex landscapes according to the cover of semi-natural habitats (e.g. Batáry et al., 2011; Tscharntke et al., 2005). Third, pollinator taxa vary significantly in their habitat requirements, especially regarding their habitat size, required natural resources and sensitivity towards management practices. The habitat quality for pollinators, as characterized by the availability of the required resources (positive) and disturbances by management practices (negative) for pollinators in their habitat range, is highly variable across flower strips and likewise across the adjacent agricultural matrix (i.e. where control sites are located) throughout Europe (Cole et al., 2017; Roulston & Goodell, 2011). Altogether, studies evaluating flower strips and their benefits for pollinators have come to different results, mostly depending on taxa requirements, spatio-temporal scales and landscape context covered in these studies (Albrecht et al., 2020; Batáry et al., 2020; Boetzl et al., 2021; Carvell et al., 2022; Ekroos et al., 2014; Jönsson et al., 2015; Schubert et al., 2022). For that very reason, it is crucial to assess the benefits of flower strips for multiple pollinator taxa collectively to aid decision-making in the implementation of effective flower strips.

In this study, we performed a systematic review of literature to assess how the benefits of flower strips for pollinating insects are related to habitat quality across European agricultural landscapes. We assessed the size of flower strips effect on pollinators reported in the literature, focusing on bees (Apiformes), butterflies (Lepidoptera) and pollinating Diptera (Syrphidae) as main pollinator taxa. Based on the 'ecological contrast' framework proposed by Kleijn et al. (2011), we hypothesized that the level of benefits reported in the literature is intimately related to the level of contrast in habitat quality between the flower strips and control treatments assessed at local scale (Figure 1). Herein, we expected the more distinct the contrast in habitat quality between flower strips and control treatments, the higher the effect size and therefore the level of benefit reported in

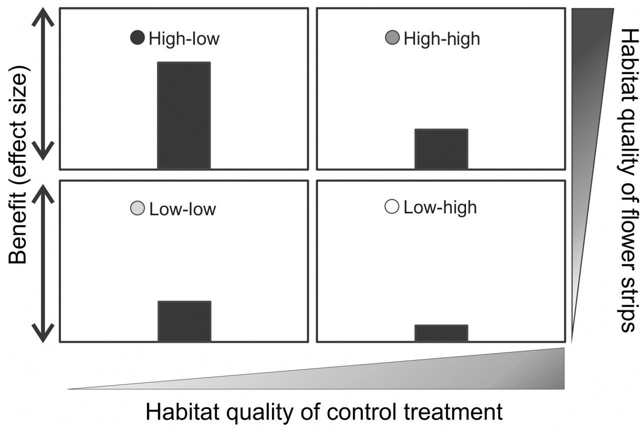

FIGURE 1 Schematic representation of the hypothesized level of benefit (effect size) of flower strips based on different levels of habitat quality contrast between strips and control treatments reported in the literature. Each treatment combination represents a habitat quality contrast subgroup color-coded to highlight high (black, white circles) or low (dark and light grey circles) levels of contrast.

the literature (Figure 1). We additionally expected that such effect size decreases in scenarios involving treatments with similar habitat quality or even cases where flower strips represent low-quality habitats, which are compared with other control types (e.g. other AES; Figure 1). We followed a meta-analytic approach to assess our hypothesis by addressing the following questions:

(Q1). Does the effect size of flower strips on pollinators increase with the level of contrast in habitat quality between flower strips and control treatments? If it is so,

(Q2). Does such pattern depend on the studied pollinator taxa? and lastly, since the effectiveness of AES for pollinators has been largely linked to landscape heterogeneity (Marja et al., 2019, 2022; Scheper et al., 2013), we asked:

(Q3). Does this effect size–habitat quality relationship vary between simple and complex landscapes?

Understanding the relationship between flower strip benefits and habitat quality contrast may enhance generalizable information regarding the effectiveness of this AES in European agricultural landscape and may provide important insights for further policy making.

2 | MATERIALS AND METHODS

2.1 | Data collection

We performed a literature search in ISI Web of Science (WoS) Core collection and Elsevier Scopus databases. The search query initially focused on studies addressing the general effects of flower strips on insects-arthropods, and was subsequently directed towards studies involving pollinator focal taxa. We followed the PICO (Population, Intervention, Comparator and Outcome) combination of search terms (Higgins et al., 2019) by including all synonym terms possible for 'flower strips' and spelling variations for 'effect' term linked to logical operators to maximize the number of relevant studies covering the effect of flower strips (Figure S1 in Supporting Information 1). We used the review by Haaland et al. (2011) as reference point and consequently limited our literature search to articles published from 2009 to early 2021 (last search date: Feb 2021) and performed in the 27 members of the EU, United Kingdom, Switzerland and Norway (EU28 + CH + NO; Figure S1). In order to minimize potential publication bias (i.e. the file drawer problem, Rosenthal, 1979) and maximize the number of relevant data sources, we also searched for national-scale articles, reports, unpublished studies, ongoing projects and potential data holders using the Google web search engine and Thünen Discovery engine tool (EBSCO Industries, 2023). We additionally targeted literature reviews published after Haaland et al. (2011), that is, Scheper et al. (2013) and Dietzel et al. (2019), for tracing back studies with relevant data sets for our research questions.

We combined results from WoS and Scopus searches, removed duplicates and added results traced from literature reviews for further title and abstract screening (172 potential studies; Figure S2). A total of 78 studies involving focal pollinator taxa remained for full-text screening (65 from WoS/Scopus search, 10 traced from literature review sources). We used the following criteria for study selection: (i) studies with experimental design contrasting flower strips with any other type of treatment (i.e. monofloral strips or areas, field margins, spontaneous vegetation margins, sown grassy strips, crop fields, grasslands; hereafter control treatment); (ii) studies reporting species richness and/or abundance results with mean values, variability measures (standard deviation, SD; standard error of the mean, SEM; or confidence interval, CI) and sample sizes for both flower strips and control treatments (cases providing between-group statistic tests were included); (iii) studies including at least three spatial replicates per treatment; and (iv) studies providing a minimal comprehensive description of treatments dimension, floral resources and management for further habitat quality characterization. A PRISMA flow diagram with the selection process (identification, screening, eligibility, inclusion) is provided in the Supporting Information (Figure S2).

We constructed a database, where each data entry corresponded to a paired result on species richness or pollinator abundance as compared between treatments (flower strip–control) per publication source. We gathered data from the main text, tables and appendixes of publications, or used WebPlotDigitizer (Rohatgi, 2022) to extract data from graphical results. In publications involving more than one treatment level or type for either flower strips or controls (e.g. treatments centres and edges, different widths or plant species mixtures), we extracted data only if such treatments corresponded to independent spatial units. In case of studies involving multi-year evaluations, we extracted data per year and treated these as independent (temporal replication) only if annual management for both treatments were involved. In these specific cases, the first year was considered as establishment year and therefore not included in our database. Similarly, studies presenting either altogether focal taxa results or separate results per pollinator group (e.g. solitary bees, bumblebees, butterflies, hoverflies) were used as independent data entries as long as they corresponded to independent sampling efforts (i.e. different methods as sweeping nets or pan traps) or events (i.e. different collecting dates). In cases of studies reporting both cumulative and separate results, we prioritized separate results for data extraction. In this sense, several studies contributed with more than one entry to both species richness and pollinator abundance database. For landscape structure description, we classified each study as having been conducted in a structurally simple or complex landscape according to a 20% cover threshold in semi-natural habitats (Batáry et al., 2011), based on the information provided or referenced in each publication. Most publications offered a comprehensive description of the surrounding landscape, and we performed a complementary visual assessment of study landscapes using Google Earth software when no information was available (sensu Scheper et al., 2013).

2.2 | Habitat quality classification

Habitat quality of flower strip and control treatments was characterized by means of a score (hereafter HQ score) based on eight parameters related to habitat dimension, floral resources and management information provided within the selected publications (Table 1). We extracted or calculated data for each parameter per publication and constructed a habitat quality database for each treatment separately (flower strips and controls). Using histograms and assessing intrinsic information provided within publications, we classified the outcome of all parameters into categories with scaled scores varying from 1 to 4 (i.e. low- to high-habitat quality) depending on each case (Figure S3; Table S1). All treatments were then assessed by assigning a parameter score according to their habitat dimension, floral resources and management features (Figure S3; Table S1). For example, in terms of habitat dimension for pollinators, a higher habitat quality is assumed for larger areas of flower strips relative to the study area and for wider flower strips, whereas larger areas of control plots relative to the study area and wider control plots are assumed to be of lower habitat quality. Herein, HQ score represented the mean value of all parameter scores within a treatment per publication (Table S1). We calculated HQ scores for both treatments per each data entry (pairing result), averaging a score value of 2.3 for flower strips (min = 1.4, max = 3.3) and 1.3 for controls (min = 1, max = 2.9) across the entire database.

In order to evaluate the difference in habitat quality between treatments assessed in the literature, we computed a hierarchical clustering for HQ scores cutting the resulting tree into two clusters (k = 2) in order to classify scores as high or low habitat quality groups (Figure S4). This procedure allowed us to recognize treatment combinations in terms of habitat quality and generated habitat quality subgroups (see Figure 1) for further analysis. In addition, to visualize a potential gradient in habitat quality contrast between flower strips and controls, we calculated a differential value of HQ, hereafter ΔHQ, by subtracting HQ score for flower strip treatment minus HQ score for control treatment at each data entry. Resulting ΔHQ values showed a gradient on habitat quality contrast from negative contrast values, highlighting low-quality flower strips versus high-quality control cases, to positive contrast values, indicating a high-quality flower strips versus low-quality control scenario. Values around zero indicated treatment combinations involving similar levels on habitat quality with no apparent contrast (high–high or low–low; Figure S5).

2.3 | Effect size calculation

We used the unbiased standardized mean difference Hegdes' g as the metric of effect size of flower strips on pollinators (Borenstein et al., 2009; Hedges, 1981). This effect size measurement is commonly used in ecological literature for comparing two means and incorporates a correction for small sample sizes, which is the case in our data (Nakagawa & Santos, 2012; Rosenberg et al., 2013). Hegdes' g and their nonparametric estimates of variance were calculated for all data entries based on the mean and variability measure (SD, SEM or 95% CI) of pollinator abundance or species richness and sample sizes reported for both treatments (Hedges & Olkin, 1985). In few cases, we calculated Hegdes' g and estimates of variance from between-group statistic tests (F- or t-tests, p values) and sample sizes provided within publications (Lipsey & Wilson, 2001; Lüdecke, 2019). Positive Hedges' g values indicated that species richness or pollinator abundance was higher in flower strips than control treatments, while negative values indicated the opposite. We described effect size as small (≥0.20), medium (≥0.50) and large (≥0.80) based on Cohen (1988).

2.4 | Meta-analyses

To address our research questions, we implemented independent multilevel random effect models setting country, study ID and entry ID as nested random factors and using restricted maximum likelihood (REML) for estimating model parameters. We included 'country' as a random term to account for the potential lack of independence among effect sizes derived from studies performed in localities under dissimilar environmental policies or regulations regarding flower strips (Haaland et al., 2011). As starting point, we fitted a model without moderators to test the general effect of flower strips compared to control treatments. Then, we fitted (i) a categorical model with habitat quality contrast subgroup as moderator to determine at which treatment combination the highest pooled effect size occurs (*Q1*); and (ii) a continuous model (meta-regression) using ΔHQ as moderator to assess the flower strip effectiveness along the habitat quality contrast gradient (*Q1*). In both models, we assessed the amount of heterogeneity variance captured by each random term (σ^2) by calculating the multilevel version of the I^2 statistic (variation not attributable to sampling

TABLE 1 Flower strips and control parameters considered for habitat quality characterization based on habitat dimension, floral resources and management (data details are provided in Table S1).

Parameter	Remarks	References
Dimension		
Relative area	Proportion of potential foraging and non-foraging areas for pollinators within each study experimental setting ([Treatment area * 100/total study area])	Haaland et al. (2011) and Scheper et al. (2015)
Width	Width of treatment strips or margins as proxy of habitat availability for pollinators	Haaland et al. (2011) and Scheper et al. (2015)
Floral resources		
Number of plants species	Number of species within treatments reported through seed mixture list or species number as proxy of food availability	Scheper et al. (2013) and Sutter et al. (2017)
Number of key floral species	Number of species within treatments that have been previously reported as 'most visited' by the focal taxa (Apiformes, Lepidoptera, Syrphidae) as proxy of food/habitat quality	Carreck and Williams (1997, 2002), Carvell et al. (2004, 2007, 2011), Haaland and Gyllin (2010), Haaland and Bersier (2011), Sutter et al. (2017) and Ouvrard et al. (2018)
Flowering time	Flowering period of plant species (based on seed mixtures) within treatments as proxy of temporal food availability	Baden-Böhm et al. (2022)
Plant life cycle	Longevity of treatment (seed mixture or plant composition) as annual, perennial or both (mixture) in order to account for pollinator preferences and temporal food availability within flower strips	Carvell et al. (2004, 2006)
Management		
Age	Number of years of the treatment establishment as proxy of habitat stability for pollinators	Haaland et al. (2011) and Schmied et al. (2022)
Management	Treatment management as extensive, intensive or special practices to account for potential effects (positive or negative) of management on habitat quality	Haaland et al. (2011), Schmied et al. (2022) and Piqueray et al. (2019)

error; Cheung, 2014). This statistic allowed us to quantify how much of the model heterogeneity is cause to differences within countries, studies and how much is caused by between-entry differences. To evaluate whether the benefits of flowers strips depend on pollinator taxa groups (*Q2*) or the surrounding landscape (*Q3*), we fitted two independent models addressing a two-way interaction between ΔHQ * focal taxa (Apiformes, Lepidoptera, Dipteran) and ΔHQ * landscape structure (Simple, Complex). We assessed any potential collinearity between moderators in each interaction model by means of the variance inflation factor, finding no correlation between factors in either species richness (VIF < 1.8) or abundance (VIF < 2.4) models.

We evaluated the sensitivity of each meta-analytic model by defining influential outliers' data entries and comparing fitted models with and without such entries (sensu Habeck & Schultz, 2015). Following Habeck and Schultz (2015), we defined influential outliers as effect sizes with hat values (diagonal elements of the hat matrix, aka leverages) greater than two times the average hat value (considered influential) and standardized residual values exceeding 3.0 (considered statistical outliers). In case of detecting influential outliers in the models, such data entries were removed and models were re-fitted. We detected no influential outliers within models for pollinator species richness data, and few within models for pollinator abundance (Table S2). Potential publication bias was explored by funnel plots interpretation, regression test for funnel plots and Rosenthal's fail-safe numbers method (Rosenthal, 1979). The regression test for funnel plot asymmetry indicated no significant publication bias for neither species richness ($z=0.48$, $p=0.63$) nor abundance ($z=0.81$, $p=0.41$) data. Rosenthal's failsafe numbers calculation indicated that more than 71,245 and 84,909 studies might be needed that the positive effect of flower strips became non-significant in both species richness and abundance data respectively.

All analyses were performed using R statistical program version 4.1.1 (R Core Team, 2021). Hierarchical clustering analysis for habitat quality classification was calculated based on Euclidean distance using vegdist and hclust functions of vegan package (Oksanen et al., 2019). Effect sizes were calculated using effect_sizes, esc_t and esc_f functions from the esc package (Lüdecke, 2019), and meta-analytical models were fitted using rma.mv function included in the metafor package (Viechtbauer, 2010). Sensitivity analyses and publication bias were also performed using the metafor package (Viechtbauer, 2010).

3 | RESULTS

3.1 | Data overview

A total of 29 studies matched our selection criteria with 21 studies providing species richness data (161 data entries) and 27 studies pollinator abundance data (189 data entries; Table S3). Selected studies used mainly crops (32%), grassy margins (29%), spontaneous vegetation strips (16%) and grasslands (11%) as control treatments, with few cases employing hedges, field margins, monofloral strips or forest (<5%) as counterpart of flower strips (Table S3). Most of the studies provided separate results by pollinator taxa group: 9 for species richness and 17 for abundance of Apiformes; 8 for species richness and 7 for abundance of Lepidoptera; and 4 for species richness and 7 for abundance of Syrphidae. Landscape structure of 22 studies was classified as simple (18 studies) or complex (4 studies), and seven studies provided non-reliable information regarding landscape (vague description or no geographical coordinates) leading to the exclusion of 42 and 52 data entries from richness and abundance databases, respectively (Table S3). All databases are provided as electronic Supplementary Material in Supporting Information 2.

3.2 | Effects of habitat quality

Overall, about 79% of the selected literature reports a positive effect of flower strips on pollinators. Our model without moderators supported these benefits of flower strips implementation and showed large positive effects of flower strips on pollinator species richness (pooled Hedge's $g = 1.24$, CI = 0.84–1.63, $p < 0.001$) and pollinator abundance (pooled Hedge's $g = 1.19$, CI = 0.66–1.71, $p < 0.01$). A three-level model provided a more parsimonious fit compared to a higher level model containing 'country' as random factor for both species richness ($AICc_{reduced} = 554.92$; $AICc_{full} = 557$) and abundance ($AICc_{reduced} = 659.5$; $AICc_{full} = 661.6$) data. This pattern remained in subsequent models, where the variance component of the 'country' term was rather low ($\sigma^2 < 0.001$). Therefore, we dropped 'country' as random factor in further meta-analysis.

Models using treatment combinations as moderators showed that the magnitude of pooled effect sizes differs among habitat quality contrast subgroups (Table 2). Combinations contrasting flower strips of high habitat quality against controls of low habitat quality showed a significant large effect size compared with the other treatment combinations (Figure 2a). Combinations involving both flower strips and control treatments with low habitat quality

TABLE 2 Summary table of meta-analytical models showing tests of moderator, residual heterogeneities, estimated variance components and models AICc.

Model	Moderators	df	Q	p	Variance components	AICc
Pollinator species richness						
	Without	160	1228.4	<0.01	$\sigma^2_{Level\ 2} = 1.25$; $I^2_{Level\ 2} = 63.3$; $k = 161$	554.9
	Moderator				$\sigma^2_{Level\ 3} = 0.52$; $I^2_{Level\ 3} = 26.3$; $k = 21$	
Categorical	Residuals	157	1076.5	<0.01	$\sigma^2_{Level\ 2} = 1.09$; $I^2_{Level\ 2} = 63.3$; $k = 161$	536.4
	Moderator	3	5.6	<0.01	$\sigma^2_{Level\ 3} = 0.70$; $I^2_{Level\ 3} = 26.2$; $k = 21$	
Continuous	Residuals	159	1031.5	<0.001	$\sigma^2_{Level\ 2} = 1.06$; $I^2_{Level\ 2} = 58.9$; $k = 161$	534.8
	Moderator	1	20.1	<0.001	$\sigma^2_{Level\ 3} = 0.54$; $I^2_{Level\ 3} = 29.7$; $k = 21$	
ΔHQ * taxa	Residuals	107	632	<0.001	$\sigma^2_{Level\ 2} = 0.98$; $I^2_{Level\ 2} = 64.6$; $k = 113$	359.8
	Moderators	5	4.6	0.001	$\sigma^2_{Level\ 3} = 0.36$; $I^2_{Level\ 3} = 23.7$; $k = 15$	
ΔHQ * landscape	Residuals	115	746.5	<0.001	$\sigma^2_{Level\ 2} = 0.78$; $I^2_{Level\ 2} = 60.2$; $k = 119$	409.5
	Moderators	3	5.4	0.002	$\sigma^2_{Level\ 3} = 1.16$; $I^2_{Level\ 3} = 29.2$; $k = 18$	
Pollinator abundance						
	Without	188	1710.7	<0.001	$\sigma^2_{Level\ 2} = 1.04$; $I^2_{Level\ 2} = 56.6$; $k = 188$	644.3
	Moderator				$\sigma^2_{Level\ 3} = 1.59$; $I^2_{Level\ 3} = 36.8$; $k = 27$	
Categorical	Residuals	183	1605.5	<0.001	$\sigma^2_{Level\ 2} = 0.97$; $I^2_{Level\ 2} = 37.4$; $k = 187$	642.6
	Moderators	3	6.7	<0.001	$\sigma^2_{Level\ 3} = 1.34$; $I^2_{Level\ 3} = 55.9$; $k = 26$	
Continuous	Residuals	184	1357.5	<0.001	$\sigma^2_{Level\ 2} = 0.99$; $I^2_{Level\ 2} = 49.1$; $k = 186$	617
	Moderator	1	15.7	<0.001	$\sigma^2_{Level\ 3} = 0.84$; $I^2_{Level\ 3} = 41.7$; $k = 26$	
ΔHQ * taxa	Residuals	166	1085.3	<0.001	$\sigma^2_{Level\ 2} = 0.93$; $I^2_{Level\ 2} = 58.4$; $k = 172$	545.8
	Moderator	5	8.2	<0.001	$\sigma^2_{Level\ 3} = 0.48$; $I^2_{Level\ 3} = 30.3$; $k = 24$	
ΔHQ * landscape	Residuals	132	88.5	<0.001	$\sigma^2_{Level\ 2} = 0.74$; $I^2_{Level\ 2} = 36.7$; $k = 136$	436.2
	Moderator	3	7.3	<0.001	$\sigma^2_{Level\ 3} = 1.25$; $I^2_{Level\ 3} = 57$; $k = 21$	

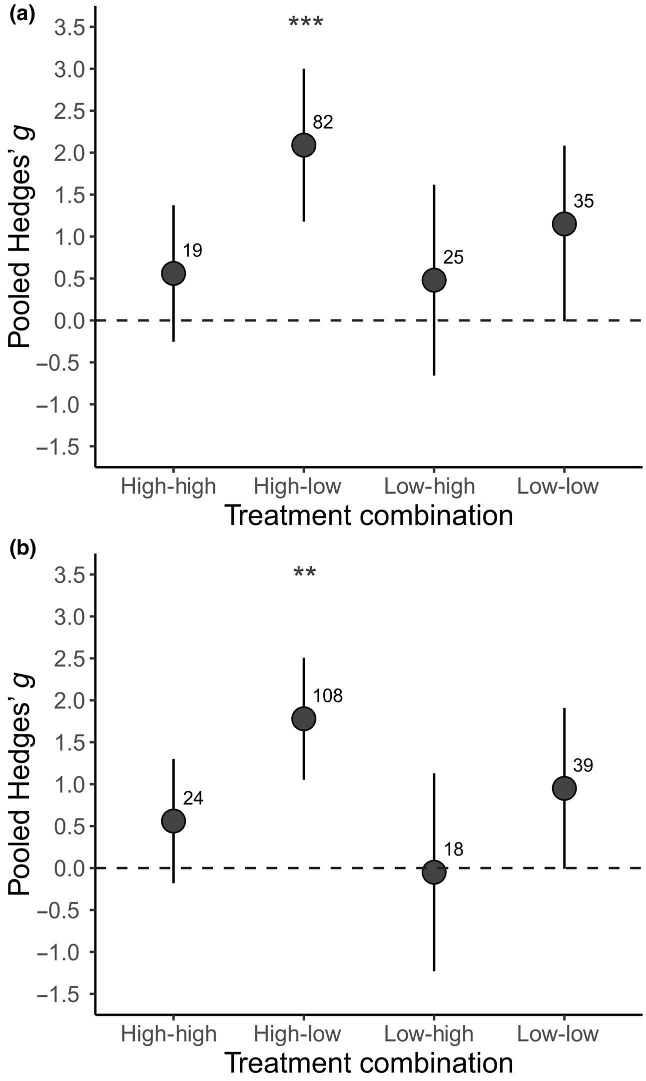

FIGURE 2 Effect of flower strips on pollinator (a) species richness and (b) abundance within habitat quality subgroups. Dots and error bars represent the pooled effect sizes (Hedges' *g*) and 95% CI for treatment combination (flower strips vs. control) in terms of habitat quality contrast (high/low vs. high/low). The effect size is significantly different from zero (**$p < 0.001$, ***$p < 0.0001$) if the CIs do not overlap with zero. Numbers near dots indicate sample size.

still showed a large but not significant effect size (95% CI overlapping zero), while subgroups contrasting treatments with similar high habitat quality or involving high quality controls showed non-significant small to medium effects on pollinators (Figure 2a). This pattern was consistent for both pollinator species richness and abundance, with slightly higher pooled effect sizes in species richness than abundance categorical model (Figure 2a,b). According to the estimated variance components, about 63% of the total variation within species richness categorical model was attributed to within-study heterogeneity ($I^2_{\text{Level 2}}$; between entries) and 26% was caused by heterogeneity between studies ($I^2_{\text{Level 3}}$; Table 2). An opposite pattern was observed within pollinator abundance categorical model with higher portion of the heterogeneity associated with between-studies component rather than between entries ($I^2_{\text{Level 3}} > I^2_{\text{Level 2}}$; Table 2). Meta-regression models indicated that the flower strip effect on pollinators is moderated by a gradient in habitat quality contrast (Table 2). Regression lines in both species richness and abundance models showed a significant increase of the effect size from negative to positive ΔHQ values (Figure 3), slightly stronger in species richness (regression slope = 1.09; Figure 3a) compared to pollinator abundance (regression slope = 0.86; Figure 3b). Effect size in data entries at $-0.5 < \Delta HQ < 0.5$ had a high weight in the regression model for species richness (Figure 3a), while effect size in data entries at $0 < \Delta HQ < 1.5$ received more weight in the pollinator abundance meta-regression (Figure 3b). In both cases, the estimated variance components suggested that 49%–59% of the variation in models can be attributed to within-study heterogeneity ($I^2_{\text{Level 2}}$) and about 29%–42% can be associated with between-study heterogeneity ($I^2_{\text{Level 3}}$; Table 2).

3.3 | Effects of habitat quality interactions with pollinator taxa and landscape complexity

The interaction model for species richness data revealed that the positive relationship between effect size and habitat quality contrast is consistent among pollinator taxa, without a significant interaction between ΔHQ and either Apiformes or Lepidoptera taxa group ($p > 0.05$), and marginally significant interaction between ΔHQ and Syrphidae group ($p = 0.06$; Figure 4a). For pollinator abundance, the interaction model showed that the increase of the effect size along the habitat quality contrast gradient depends on the taxon group (Figure 4b), being significantly stronger in Lepidoptera ($p = 0.008$) than other pollinator taxa groups (Figure 4b). Non-significant interactions between ΔHQ and landscape structure moderators were detected within interaction models for either species richness ($p > 0.42$) or pollinator abundance ($p > 0.7$), and the magnitude of the effect size along the gradient of habitat quality contrast did not vary between simple and complex structured landscapes (Figure 4c,d). Estimated variance components within interaction models suggested that model variation is mostly associated with heterogeneity at entries level ($I^2_{\text{Level 2}} > 58.4$) than between studies ($I^2_{\text{Level 3}} < 30.3$), with exception of the landscape interaction model for pollinator abundance, where most of the variation was attributed to between-study heterogeneity (Table 2).

4 | DISCUSSION

4.1 | Effective flower strips for pollinators

Our meta-analysis provides clear evidence that the effectiveness of flower strips reported in previous studies depended on the quality of pollinator habitats in flower strips and control treatments. The effect size of flower strips was highest for the treatment combination high–low

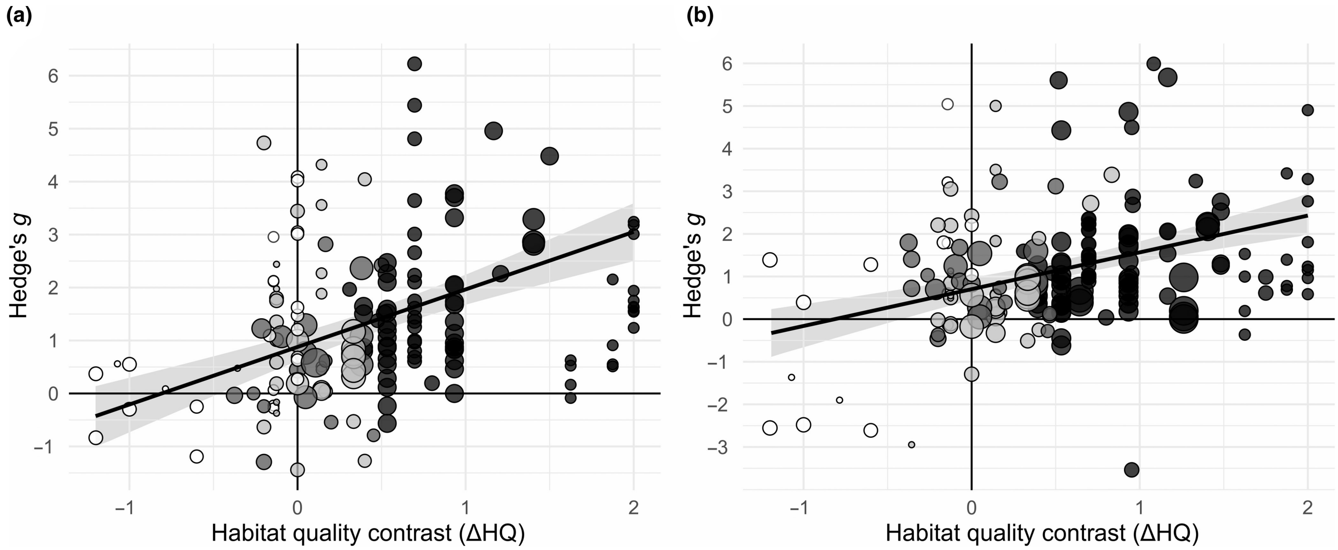

FIGURE 3 Relationship between effect size (Hedge's *g*) of flower strips and the gradient on habitat quality contrast (ΔHQ) for pollinator (a) species richness and (b) abundance. Solid line and shaded area show the estimated effect and 95% CI according with meta-regression models. The size of each circle represents the inverse variance (non-parametric estimate) weight applied to each data entry in the model. Circle colors highlight habitat quality subgroups: high–low in black, high–high in dark grey, low–low in light grey, low–high in white.

(flower strips vs. control) and lowest for the combination low–high, as hypothesized (Figures 1 and 2). In high–low combinations, flower strips provided high-quality habitats attracting pollinators that can hardly find resources at the low-quality control habitat. In low–high combinations, on the contrary, flower strips did not attract pollinators much, because there were abundant resources for pollinators at the control habitat, whereas only few resources were added to the landscape by the low-quality flower strip. This is in line with the findings of Scheper et al. (2013) that higher AES effectiveness was related to higher ecological contrasts as established between AES and control fields.

The general relationship between flower strip effectiveness and the contrast in habitat quality between flower strips and control treatments remained rather independent of pollinator taxa, similar to the findings of Scheper et al. (2013), although we found a stronger correlation for the species richness of Syrphidae as compared to Apiformes and Lepidoptera as well as for the abundance of Lepidoptera as compared to Apiformes and Syrphidae (Figure 4a,b). These results point to further taxa-specific habitat requirements, which could not be differentiated within our meta-analysis, but are essential to be considered when implementing flower strips to promote specific pollinator taxa (Scheper et al., 2021). Although landscape complexity, as described by seminatural habitat proportion in the surrounding landscape, has been highlighted as important factor for flower strip effectiveness (Haenke et al., 2009; Scheper et al., 2013; Krimmer et al., 2019; Warzecha et al., 2021; but also see Boetzl et al., 2021), we did not find evidence for any interaction between habitat quality contrast and landscape complexity that would be related to flower strip effectiveness (Figure 4c,d).

Provided that control treatments are usually selected to represent a part of the surrounding agricultural matrix not linked to flower strips (Table S3), our results indicate that flower strips were particularly effective, when located in an agricultural matrix of low habitat quality (Figures 2 and 3). However, pollinators can still benefit from flower strips in agricultural landscapes of high habitat quality. Previous studies have shown that pollinator species richness and abundance on flower strips were higher with more heterogeneous agricultural landscapes around, characterized by diverse, rather extensive land use and woody features (Grass et al., 2016; Hellwig et al., 2022; Korpela et al., 2013). Consequently, flower strips can be effective for pollinators in agricultural landscapes of high habitat quality, but they need to be well designed, either to provide complementary floral resources that are lacking throughout the landscape or to enhance niche overlap in floral resources to account for spatiotemporal patterns of pollinators (Burkle et al., 2020) and to reduce competition (Doublet et al., 2022). In this view, our results highlight the importance to consider pollinator habitat requirements in the implementation of flower strips (according to Table 1), as high habitat quality in flower strips generally enhanced their effectiveness for pollinators (Figures 2 and 3). Regarding the composition of floral resources, several key plant species have been reported to be visited by pollinators especially frequently (Table S4, see also Warzecha et al., 2018). Such a list can be used together with information on site factors, such as local climate and soil fertility, to derive region-specific recommendations for native seed mixtures (Schmidt et al., 2020, 2022). Regarding flower strip management for pollinators, previous studies have advocated for perennial flower strips over 3–5 or more years, periodic mowing and potential re-sowing after a couple of years, depending on the landscape context (Albrecht et al., 2021; Haaland & Bersier, 2011; Kirmer et al., 2018; Pywell et al., 2011; Schubert et al., 2022).

Based on our results, effective flower strips require that their locations are selected based on the habitat quality of the agricultural matrix and that flower strips are established and managed based on the habitat requirements of target pollinator taxa (e.g. in terms of floral resources and taxa-specific life cycles). In terms of their design, implementation and management, it appears to be less difficult to achieve effective flower strips for pollinators in agricultural landscapes of low habitat quality. Nevertheless, including the results of Albrecht et al. (2020), targeted measures that allow re-establishment and survival of pollinator populations in low-quality agricultural landscapes need to be designed for the long term, including a landscape-scale network of perennial flower strips and seminatural features (Krimmer et al., 2019). Altogether, to achieve effective flower strips for pollinators also in agricultural landscapes of high habitat quality, we recommend to develop more differentiated AES in the European CAP, for example, specifying regional flower seeds based on the preferences of target pollinator groups, and advanced training of farmers in pollinator ecology.

4.2 | Gaining evidence on flower strip effectiveness in agroecological research

Recommendations how to implement effective flower strips for pollinators rely on previous studies, in which pollinators were usually compared between plots in areas with flower strips versus areas without flower strips (independent control treatments). Sometimes pollinator survey plots were located directly within flower strips, sometimes in the agricultural setting of flower strips (see also Zamorano et al., 2020). Survey plots on control treatments were also highly variable, including for example spontaneous vegetation margins as well as crop fields (Table S3). These different study designs make it hard to compare and generalize findings of individual studies included in our meta-analysis. Furthermore, biases in the

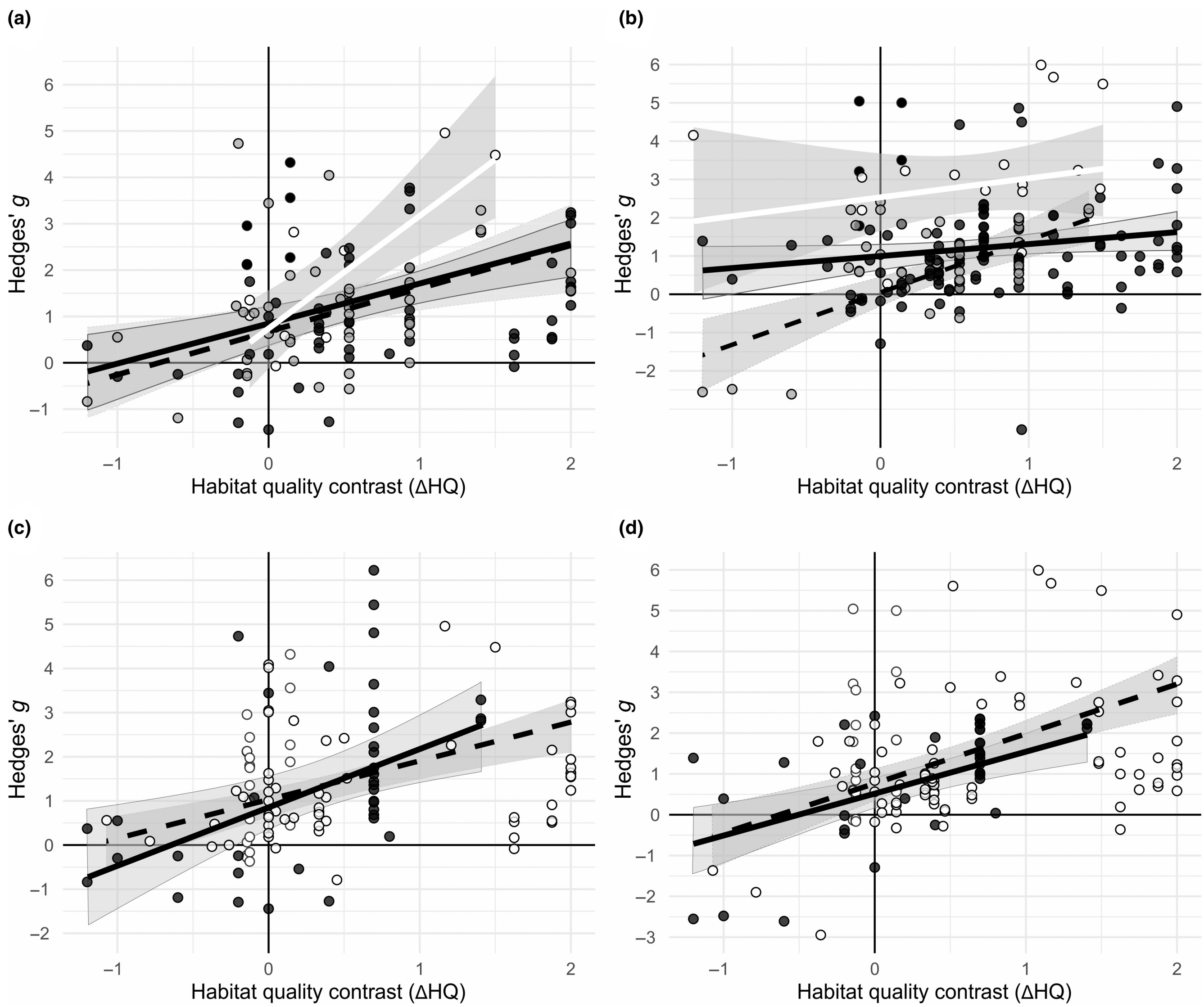

FIGURE 4 Effect size (Hedge's *g*) of flower strips relationship with moderators in interaction models. Upper panel shows results for the ΔHQ: pollinator taxa interaction for (a) species richness and (b) abundance. Regression lines, shaded areas and data points show interaction effect, 95% CI and observed effect size values by Apiformes (solid black; black-filled dots), Lepidoptera (dotted black; grey-filled dots) and Syrphidae (solid white; white-filled dots) groups. Bottom panel shows results for the ΔHQ: landscape structure interaction for (c) species richness and (d) abundance. Regression lines, shaded areas and data points show interaction effect, 95% CI and observed effect size values in complex (solid black; black-filled dots) and simple (dotted black; white-filled dots) landscapes.

choice of plots in flower strip areas and control areas cannot be excluded, as already noted in previous review studies on the effectiveness of flower strips and other AES (Josefsson et al., 2020; Kleijn & Sutherland, 2003).

For the purpose of our meta-analysis, the contrast in habitat quality between flower strips and control treatments (Figures 2 and 3) allows to integrate those different study designs. However, our results suggest that the selection of flower strips and control treatments is decisive for the outcome of individual field studies on flower strip effectiveness; thus, in these studies, it is of fundamental importance that control treatments are selected thoroughly representing those land use options that flower strips should be evaluated against. Statements about flower strip effectiveness are only valid for the tested set of control treatments. Therefore, to allow general conclusions on flower strip effectiveness for pollinators, it is necessary to survey pollinators on different control plots representing all land use types of the agricultural landscape. Moreover, results on flower strip effectiveness for pollinators should always be presented in the context of pollinator habitat quality. This includes parameters describing the dimension, floral resources and management of flower strips and control treatments (Table 1), and also the overall spatial landscape context. Batáry and Tscharntke (2022) have clearly shown how results on flower strip effectiveness for pollinators depend on the type and spatial scale of control treatment and flower strip.

Despite a large number of studies on flower strip effectiveness for pollinators that have been compiled for our meta-analysis and in previous review studies (Albrecht et al., 2020; Haaland et al., 2011; Lowe et al., 2021; Zamorano et al., 2020), the scientific understanding of the determinants of flower strip effectiveness for pollinators is still limited. Our findings illustrate that there are still specific combinations of contrast levels in habitat quality, especially with high habitat quality in control treatments, underrepresented in previous research on flower strip effectiveness for pollinators (Figures 2 and 3). Likewise, the diversity of pollinator taxa has been unevenly represented in previous studies (Figure 4). Therefore, to advance research on flower strip effectiveness for pollinators, we recommend that future studies (i) consider different contrast levels in habitat quality between flower strips and control treatments, (ii) integrate control sites under different land use types representative of the agricultural landscape, (iii) integrate flower strips under different seed mixtures, ages and management regimes (e.g. in terms of mowing), (iv) report results separately for different pollinator taxa, (v) consider different landscape contexts of flower strips and control treatments at multiple spatial scales and (vi) clearly communicate the limited study context that evidence on flower strip effectiveness is gained for.

5 | CONCLUSIONS

Pollinator habitats in agricultural landscapes are nowadays often rare and scattered. Promoted as AES, flower strips are an attractive measure to especially enhance floral resources for pollinators. Our findings suggest that the effectiveness of flower strips for pollinating insects in agricultural landscapes depends on the established contrast in habitat quality. This pattern applies across different pollinator taxa (i.e. bees, butterflies and hoverflies) and across the gradient from simple to complex landscapes. On the one hand, this implies that effective flower strips need to provide a high habitat quality for target pollinators. The financial promotion of flower strips managed for a long-term provision of diverse, complementary resources, should be prioritized. On the other hand, researchers designing future studies need to be aware of the relationship between the effectiveness of flower strips for pollinators and the contrast in habitat quality. Control treatments need to be selected thoroughly according to the research questions, and results on flower strip effectiveness always need to be reported with reference to the characteristics of flower strips and control treatments as pollinator habitats.

AUTHOR CONTRIBUTIONS

Antonio J. Pérez-Sánchez was involved in conceptualization, methodology, validation, formal analysis, writing—original draft, writing—review and editing; Boris Schröder was involved in methodology, writing—review and editing; Jens Dauber was involved in conceptualization, writing—review and editing; Niels Hellwig: was involved in writing—original draft, writing—review and editing. All authors gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information 1. Figure S1. Schematic representation of the search query. We used different combinations of resource and dimension sub-terms in quotation marks (" ") to include approximate or loose phrases and account for synonyms of flowers trips. A wild card (*) was used in the term effect to get results with spelling variations in every basic search query.

Figure S2. PRISMA flow diagram representing the flow of information through the decision process (i.e. the number of studies identified, rejected and accepted). Publications exclusion criteria is stated in the main text.

Figure S3. Schematic representation of the habitat quality classification procedure.

Figure S4. Habitat quality classification for flower strips and control treatments. Cluster analysis was performed using Euclidean distances and ward.D2 agglomeration method.

Figure S5. Delta HQ values per dataset. Dots represent ΔHQ values calculated for each data entry (flower strips HQ score—control HQ score), color-coded by treatment combination in terms of habitat quality contrast (see Figure 1). Red square represents mean value.

Table S1. Habitat quality parameters outcome and scores for both flower strip and control treatments. HQ score per publication or data entry represents the mean value of all parameter scores within a treatment.

Table S2. Meta-analytical models for abundance data before influential outliers removal.

Table S3. Summary information of the publications selected for meta-analysis. Reference identification code (ID) and the number of data entries (a paired result between flower strip and control treatments) for both species richness (S) and pollinators abundance (A) databases are provided.

Table S4. Plant species with high frequency of visitation by pollinating insects.

Supporting Information 2. Data overview extracted from studies included in the meta-analysis.

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