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Received: 3 October 2025 | Revised: 11 May 2026 | Accepted: 24 May 2026

DOI: 10.1111/cobi.70366

Conservation Biology

CONTRIBUTED PAPER

Synthesis of Pollinator-Friendly Management in European Protected Areas

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Article Impact Statement: Pollinators and the management actions to conserve them need to be enhanced in protected areas to advance European conservation strategies.

Funding information
European Union's Horizon 2020, Grant/Award Number: 101003476; Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences; Deutsche Bundesstiftung Umwelt; gemeinnützige Verlagsgesellschaft mbH; Biodiversity Monitoring South Tyrol project by Autonomous Province of Bolzano/Bozen; Specific project PřF, Grant/Award Number: UHK 2101/2024; Austrian Academy of Sciences, Grant/Award Number: 10470; European Union's Horizon Europe, Grant/Award Number: 101082101; Excellence Project of PřF, Grant/Award Number: UHK 2202/2025; Landesgraduiertenförderug; Ministry of Culture and Innovation of Hungary; National Research, Development and Innovation Fund; Safeguard: Safeguarding European wild pollinators

Abstract

Pollinators are important to humans and nature due to their role in ecosystem functioning and services. Research on the effects of pollinator management in protected areas is insufficient compared with that on farmlands and urban areas, potentially hindering appropriate policy implementation. We addressed this knowledge gap by conducting a data-based synthesis on measures to promote pollinators (especially bees, butterflies, and flies) across European protected areas. To compare the effects of management practices that enhance pollinators (pollinator-friendly; treatment) and those not focused on pollinators (conventional; control) in protected areas, we used vegetation, floral resource, and pollinator datasets. Our synthesis involved 10 countries, 34 datasets, and 639 sampling sites with different management activities (land abandonment, mowing, grazing, mulching, flower sowing, gap creation, and uprooting and girdling trees) and habitats (grasslands, forests, reed beds, and sandpits). Pooled analysis indicated that pollinator-friendly management had mainly neutral effects on floral resources and pollinators, with some positive effects but no negative effects. Dataset-level details revealed mostly neutral effects from pollinator-friendly management with some positive (15%) and fewer negative (3%) effects. Management slightly improved pollinator overall abundance and species richness, particularly for butterflies and wild bees (excluding bumblebees). Comparing our synthesis with previous studies suggests that implementing management practices for pollinators in protected areas is more challenging than in farmlands and cities, possibly because protected areas already host higher quality habitats. Alternatively, pollinator-friendly approaches commonly implemented in protected areas may be insufficient. Although the Nature Restoration Regulation provides new opportunities for pollinator conservation, implementation will require careful planning for target areas, as effective management, including pollinator requirements, requires more focused and context-specific measures than those applied in cities and farmlands. Although focused on Europe, our synthesis provides broadly applicable lessons for pollinator conservation in other highly modified landscapes but with adaptation to local ecological and socioeconomic conditions.

KEYWORDS
abandonment, biodiversity conservation, forest management, grassland, grazing, meta-analysis, mowing, Natura 2000

INTRODUCTION

Pollinating insects are a flagship group for nature conservation due to their high diversity, sensitivity to anthropogenic change, and key role in pollinating plants that support healthy terrestrial ecosystems and sustainable food production (IPBES, 2016; Oberhauser & Guiney, 2009). The decline in pollinators has driven considerable research on their ecology, population trends, anthropogenic drivers, and mitigation options (Potts et al., 2010). Because of serious concerns about the loss of pollinator diversity and jeopardized food security, pollinator-friendly management is increasing in agricultural and urban landscapes (Boetzl et al., 2021; Corbet et al., 1991; Vanbergen et al., 2020). On farmlands, pollinator-focused ecological

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management is mainly supported through agricultural policy (Kovács-Hostyánszki et al., 2017) that includes flower strips and margins (Albrecht et al., 2020; Marshall, 2005), set-asides (Kovács-Hostyánszki et al., 2021), and organic farming (Carrié et al., 2018). Cities implement similar but smaller-scale solutions through green infrastructure and involve diverse stakeholders, citizens, and funding sources (Baldock, 2020; Süle et al., 2025). Agricultural and urban initiatives focused on pollinator ecosystem services can be effective and rewarding (Kovács-Hostyánszki et al., 2017), yet they tend to favor generalist pollinator species (Süle et al., 2025). In contrast, the survival of rare and threatened pollinator species primarily depends on seminatural habitats (Maurer et al., 2022) that are often located within protected areas.

Protected areas are more widely colonized by pollinator species than unprotected areas, suggesting their importance in providing habitat and floral resources (Cooke et al., 2023; Watson et al., 2014). Although pollinators are declining across all landscape types (Cooke et al., 2023), their conservation in general often appears to be secondary to efforts to enhance pollination services in degraded environments (Kleijn et al., 2011; Wenzel et al., 2020). However, effective conservation strategies to support pollinators and improve habitat quality require coordinated and complementary actions across protected and unprotected landscapes (Kleijn et al., 2020).

Protected areas cover 16% of terrestrial ecosystems globally (Zabala et al., 2024) and 26% of these systems within the European Union (EU) (Spiliopoulou et al., 2023), with substantial differences (13%–41%) between countries (European Environment Agency, 2025). EU biodiversity policies aim to have >30% of these areas under protection, with one-third under strict protection (CBD, 2022; European Commission, 2025). Despite these goals, protection status, habitat quality, management requirements, and anthropogenic impacts vary from country to country and from site to site, and seminatural habitats face multiple threats that endanger pollinators (Dudley, 2008; Nicholson & Egan, 2020). Moreover, conservation has often overlooked insects, concentrating traditionally on vegetation and vertebrates (Chowdhury et al., 2023).

Information about the effectiveness of different habitat management practices within protected areas for pollinator conservation is still limited, except for a few charismatic butterfly and bee species (Geldmann et al., 2018; Nava-Bolaños et al., 2023). Further, major pollinator groups (e.g., most wild bees and hoverflies) are missing from the European Habitats Directive (Annex IV; European Council, 2007). These shortcomings are likely due to the widespread belief that ecological processes in protected areas are functioning well and that habitats and biodiversity in these areas exist under favorable conditions (Casanelles-Abella et al., 2023; Chowdhury et al., 2023). However, this view should be challenged (Ellerbrok et al., 2025). For example, the potential long-term effect of extinction debt has not fully been considered (Krauss et al., 2010; Löffler et al., 2020). In addition, Natura 2000 designations have been criticized for not considering pollinator habitat requirements (Baldock et al., 2015; Theodorou et al., 2025). Given the important functional role of pollinators, nature conservation should integrate pollinator-focused solutions into protected habitat management plans, especially if the area is expanding with new designations.

To improve pollinator conservation in protected areas, guidance can be drawn from ongoing measures in agricultural and urban habitats. However, unlike the relatively simpler management contexts of farmland and cities, management plans for protected areas need to consider more diverse habitat and vegetation types and specific, sometimes complex, protection goals (Gaston et al., 2008; Geldmann et al., 2018). Additionally, to understand the contribution of protected areas to pollinator conservation, both landscape-level differences and long-term changes in pollinator diversity need to be examined (Baldock et al., 2015), and the effectiveness of different management actions to promote pollinators also needs to be considered (Süle et al., 2025). Therefore, case studies and reviews of protected area effectiveness from a pollinator perspective are essential (Leverington et al., 2010; Watson et al., 2014).

Several protected area management practices, even those not originally designed for pollinator conservation, are already in use that could support pollinators. For example, extensive grassland management in protected areas provides continuous floral resources, suitable nesting habitat for ground-nesting bees, and less-disturbed environments throughout the year (Albrecht et al., 2007; Schwarz et al., 2023). Among these practices, extensive grazing results in more structured, heterogeneous vegetation (Hopfenmüller et al., 2014), and extensive mowing leads to higher, more closed, homogeneous vegetation (Kőrösi et al., 2014; Révész et al., 2025). Abandonment (similar to agricultural set-asides) can also be pollinator-friendly management during certain periods, although it is not suitable for all grassland types and regions (Slancarova et al., 2016; Walcher et al., 2019). Typically, optimal mowing or grazing intensity is necessary to maximize plant and associated pollinator diversity and prevent vegetation degradation, late succession processes (e.g., scrub encroachment; Ernst et al., 2017; Mora et al., 2022), and non-native plant invasion (Kőrösi et al., 2014). Habitat restoration in protected areas that relies on natural processes (e.g., succession) or active interventions (e.g., sowing seeds of insect-pollinated plants) could also result in higher habitat quality for pollinators (Eckerter et al., 2021; Hedberg & Kotowski, 2010; Heneberg et al., 2013; Poniatowski et al., 2020). Pollinator conservation studies often concentrate on grasslands in protected areas, yet other types of protected areas also hold considerable potential for pollinators (Kudrnovsky et al., 2020). Floral and nesting resources in woodlands could be boosted by restoration and specific forest management actions, such as gap-cutting (Eckerter et al., 2022; Kozel et al., 2021; Sebek et al., 2015), coppicing (Fartmann et al., 2013; Weiss et al., 2021), and deadwood-enhancing approaches (Eckerter et al., 2021). Reed beds and quarries (e.g., sand pits and gravel pits) can also be important and improved for pollinators (Bogusch et al., 2020; Heneberg et al., 2013). In addition to local-scale management interventions in protected areas, a diversified landscape with complementary resources also plays an important role for pollinators (Eckerter et al., 2022). Additionally, a key advantage of protected areas is that conservation management is unlikely to

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be in conflict with food production, a concern in agricultural areas, thus increasing opportunities to protect rare and threatened pollinator species (Chowdhury et al., 2023; Cooke et al., 2023).

Maintaining higher biodiversity and halting the decline in pollinating insects are priorities for many stakeholders, including national parks, international nongovernmental organizations, and governments in the EU (Hering et al., 2023; UN DESA, 2023). Europe has experienced significant biodiversity loss (Hermoso et al., 2022), but attention is now shifting toward ensuring, restoring, and expanding well-functioning protected areas (CBD, 2022; Council of the EU, 2023; European Parliament, 2024). These goals should be based on robust evidence and region-specific implementation due to the socioeconomic and ecological differences across Europe (Batáry et al., 2010; Csákvári et al., 2021). Despite the recent pollinator-related findings from case studies, reviews, and EU pollinator monitoring (Glenny et al., 2022; Nehybová & Horák, 2024; Settele et al., 2024), a comprehensive quantitative synthesis of pollinator-friendly management in protected areas is still lacking (Diengdoh et al., 2023; Schlesinger et al., 2023).

To address this knowledge gap, we assessed the effectiveness of pollinator-friendly management in protected areas across Europe. We carried out a reanalytical data synthesis based on 34 primary datasets from 10 countries. Compared to classical, literature-based meta-analysis, a reanalytical data synthesis provides a more detailed understanding of where robust models incorporate dataset- and site-level variations in annual and seasonal factors using raw data (Riley et al., 2023; Süle et al., 2025). This approach increases engagement with the original data owners that conducted data collection, and the owners provide high-resolution published and unpublished datasets and local insights. The downsides of this approach are that gathering primary datasets is labor-intensive (Tudur Smith et al., 2016) and that datasets can be missed.

Our research aimed to determine how pollinator-friendly management in protected areas affects vegetation, floral resources, and a broad range of pollinator groups (i.e., bees, butterflies, moths, and flies). To identify general trends and specific local differences, both pooled and dataset-level differences were analyzed between treatment (pollinator-friendly management) and control (conventional management/not beneficial to pollinators) sites. We hypothesized that compared with the control practices, the pollinator-friendly management practices would have a positive effect on vegetation height and cover and on the abundance and species richness of both pollinators and their floral resources. Our large-scale datasets and collective expertise in pollinator ecology and pollinator conservation and restoration across Europe enabled us to consider a range of perspectives and the effectiveness of pollinator management and protection actions to develop transferable lessons for other highly modified landscapes worldwide, such as North America and Australia, where the climate, seminatural habitats, management practices, and plant-pollinator systems are broadly similar (Diengdoh et al., 2023; Schlesinger et al., 2023).

METHODS

Data query and selection criteria

To carry out reanalytical data synthesis, we collected available datasets of European pollinator-friendly management in protected areas. We focused on management actions that enhance resources for pollinators (e.g., any changes in habitat management that potentially promote pollinators: reducing land use intensity, restoring ecosystems, changing mowing and grazing regimes, sowing seeds of insect-pollinated plants in grasslands, and altering conventional silvicultural practices, such as gap cutting). Our aim was not to complete a systematic literature search but to identify authors with relevant datasets that potentially matched our research objectives. We searched the Web of Science Core Collection (SCI-EXPANDED; https://www.webofscience.com) using a combination of three search string groups: habitat management, pollinators, and protected habitats (Appendix S1). Despite an extensive search, it was not exhaustive, and not all relevant studies were likely captured. Ultimately, we identified authors (not papers) from whom we could access original data; thus, the obtained information was mostly based on data availability.

We found 1222 publications on 8 March 2023 and selected publications that were potentially relevant based on their titles, abstracts, and full texts. We ensured the studies met the following inclusion criteria: contained sampled abundance and species richness of pollinators, investigated any type of seminatural habitats under conservation protection, were conducted in Europe, included different management intensities, and involved at least three treatment sites (pollinator-friendly management) and three control sites (conventional management/not beneficial for pollinators). To obtain a coherent dataset focused on pollinating insects with similar sampling techniques for imagos, we excluded studies that focused exclusively on nonpollinating insect life stages (e.g., butterfly and hoverfly larvae). We included datasets from sampled sites in Natura 2000 areas (EEA, 2026), International Union for Conservation of Nature (IUCN) Protected Area Management Categories (Dudley, 2008), United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserves (UNESCO, 2026), and other international and national categories (Appendix S2; UNEP-WCMC & IUCN, 2026). To reach authors with suitable datasets, we contacted the corresponding authors of all 79 selected papers that met our criteria. To access unpublished data, we also contacted colleagues working on this topic and the network of researchers within and beyond the Safeguarding European Wild Pollinators project (https://www.safeguard.biozentrum.uni-wuerzburg.de). We requested data from 88 data owners in several repeated rounds between 1 October 2022 and 1 May 2023. Of the 88 data owners contacted, 44 responded, and 24 lacked suitable datasets for our synthesis. We offered coauthorship to the data owners and included their insights and suggestions. Finally, we gathered 34 datasets that fit the scope of this study.

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Datasets

We requested data on study design (e.g., management and habitat types), vegetation height, vegetation cover, and abundance and species richness of floral resources (i.e., insect-pollinated plants) and pollinator groups (i.e., honey bees, bumblebees, other wild bees, butterflies, hoverflies, other flies, and beetles; Appendix S2) from the data owners that contributed data. We gathered data at the highest possible resolution (e.g., site and sampling period level), including information on sampling dates. Due to differences in sampling protocols and data structures among primary datasets, we standardized and merged the names of variables for analyses (Appendix S2). Thus, herbaceous vegetation height included the average height and the maximum height in one dataset. Vegetation cover included not only the percentage of the green parts of all herbaceous plant species but also the green cover of insect-pollinated, currently flowering plants in four datasets (one was only bilberry cover and another was a categorical value). These vegetation attributes were requested as simple proxies for general habitat conditions. Flower abundance included the number of flower units, flower cover (two datasets), and categorical flowering intensity (four datasets; Appendix S2). Additionally, we calculated the total abundance and species richness for all pollinators where >1 pollinator group was sampled. Variables were consistent within each primary dataset.

The compiled primary datasets were collected between 2022 and 2003 across 10 countries, with 639 sampling sites in Europe (Figure 1 & Appendix S2). The datasets contained information on the effects of pollinator-friendly management on vegetation height (11 datasets), vegetation cover (10), and flower abundance (abu: 13) and species richness (spr: 7) for honey bees (abu: 15), bumblebees (abu: 14, spr: 14), other wild bees (abu: 16, spr: 16), butterflies (abu: 21, spr: 24), hoverflies (abu: 8, spr: 8), other flies (abu: 1, spr: 1), beetles (abu: 5, spr: 5), and total pollinators (abu: 17, spr: 17; see Figure 1 & Appendix S2). Although moths and beeflies were initially considered, no data were obtained; instead, data were available for beetles and other flies. Beyond the main groups (i.e., bees, butterflies, and hoverflies), data for other pollinators are limited in general (Rader et al., 2020). The investigated pollinator-friendly management actions were abandonment (six datasets), extensive mowing and grazing (22 datasets, of which seven contain both management types), extensive mulching (one dataset), sowing of flowering plants (one dataset) in herbaceous vegetation, and gap creation (three datasets) or uprooting and girdling trees (one dataset) in forests (Figure 1 & Appendix S2). Twenty different national or international protected area categories were in the datasets, with sites also having more than one category. In most cases, the categories were Natura 2000 (91% of datasets), national park (50%), nature reserve (47%), landscape protection area (38%), and UNESCO Man and the Biosphere reserve (35%; Appendix S2). Protection status, conservation aims, and management intensity, as well as the differences in these factors between the control and treatment sites, varied by dataset depending on the local environmental circumstances. For example, extensive mowing might have been preferred as a conservation practice over abandonment or intensive mowing, whereas abandonment might have been an alternative to any previous management action, depending on the habitat types (Figure 1 & Appendices S2 & S3). Approximately one-third of the study designs were originally control-treatment approaches (i.e., discrete management categories), whereas the remainder of the designs were categorized for this study based on expert decisions or treatment gradients according to the management frequency and intensity (Appendix S2). The habitat types in the datasets were grasslands (27 datasets), forests (five datasets), reed beds (two datasets), and sand pits (one dataset) (Figure 1 & Appendix S2). Despite these differences in study design, habitat types, and intensity and level of management, the treatments consistently aimed to improve habitat conditions. Therefore, their overall effects on vegetation, flowers, and pollinators were examined through pooled and dataset-level analyses.

Statistical analyses

The original data in the studies were gathered with different sampling methods, resulting in inherent variation in the response variables across datasets. To allow comparisons among datasets, we considered the datasets and sites as random factors in mixed models and scaled all variables between 0 and 1. The goal of scaling was to make the datasets comparable so that appropriately structured models could be used for our main study question on the differences between treatment and control sites. We scaled each variable separately for each sampling period within the datasets between 0 and 1. Sites with values closer to 1 indicated they were the most favorable in terms of vegetation, floral resources, and pollinators, and sites with values closer to 0 indicated they were the least favorable sites. We scaled and analyzed 17 response variables separately: vegetation height, vegetation cover, flower abundance, and flower species richness and abundance and species richness of seven and six pollinator groups, respectively. Only one dataset included other flies; this group was not analyzed separately but was included in the total pollinator variables.

In our analyses, we applied generalized linear mixed models (GLMMs) (Zuur et al., 2009) with an ordered beta family to model the 0–1 values, allowing lower and upper bounds (Kubinec, 2023). To account for issues with data independence (e.g., using different methodologies) within studies and variances over the sampled years, dataset and year were included as random factors. We examined both the overall and dataset-level differences between treatment (pollinator-friendly management) and control (conventional management/not beneficial to pollinators) sites. First, to determine the general effects of pollinator-friendly management, we combined datasets and analyzed the response variables separately (pooled analyses). Pollinator-friendly management (treatment vs. control sites) was the explanatory variable (i.e., treatment effect), whereas separate primary datasets and sampled sites of the dataset (1|dataset/site), as well as sampled

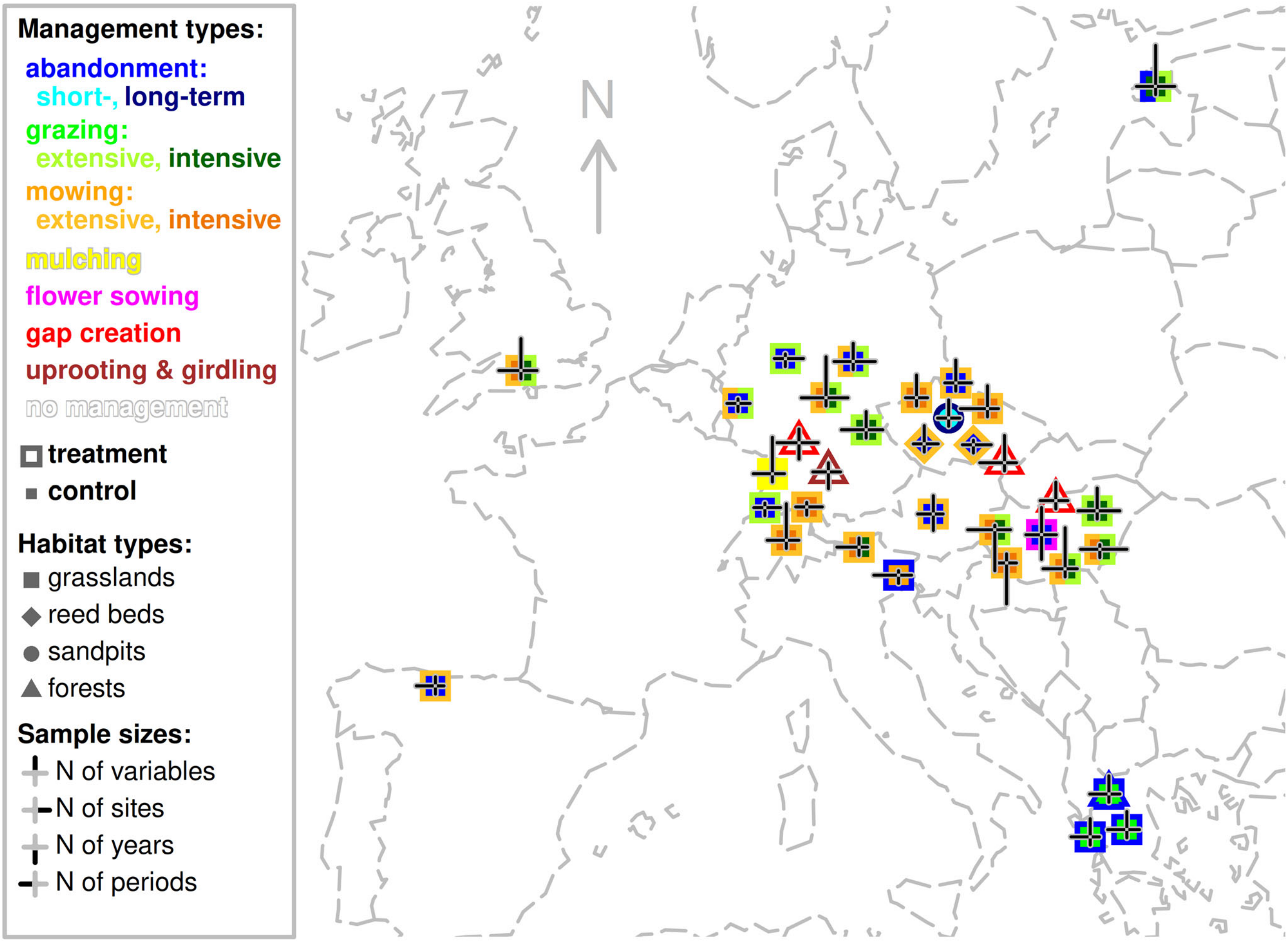

FIGURE 1 Management, habitat, and sampling details of the 34 datasets on pollinator-friendly management in protected areas across Europe. Colored points represent the studies with their averaged site coordinates, jittered within countries for visualization. Double colors mean more than one management type among the treatment and control sites in a dataset. Controls are the internal colors, whereas treatments are the external color of the symbols. The lengths of four-way lines illustrate the relative rate of the sample sizes in each dataset: black upward line (number of sampled variables, i.e., 1–9), black right line (number of sites, i.e., 6–60), black downward line (number of sampled years, i.e., 1–5), and black left line (number of sampling periods within a year, i.e., 1–6). EuroGeographics for the administrative boundaries.

years and sampling periods of the dataset (1|year/period), were treated as two groups of separately nested random factors. To control for multiple testing, we calculated adjusted *p* values using the method of Benjamini and Hochberg (1995). Second, to identify the specific differences between datasets, we fitted similar models, including the treatment effect for each dataset, and incorporated them into one model, improving standard error estimates and preventing increased Type I errors due to multiple testing (dataset-level analyses). Explanatory variables were the datasets with reference to zero and the interaction between datasets and pollinator-friendly management (i.e., ~0+dataset+dataset:treatment). The sampled sites, years, and sampling periods were random factors ([1|site]+[1|year/period]). Our analyses aimed to determine whether pollinator-friendly management had a positive, negative, or neutral effect on the vegetation height and cover, floral resources, and abundance and species richness of pollinators. Furthermore, to demonstrate the magnitude of their effects, robustness, and significance, we extracted odds ratios (the exponential of model estimates), with 95% confidence intervals and original and adjusted *p* values from the GLMMs. We also calculated Cohen's *d*, which is the difference between two group outcomes divided by the standard deviation (Cohen, 1969; Ferguson, 2009) and can be classified as a negligible ($d<0.2$), small ($d = 0.2$–0.5), medium ($d = 0.5$–0.8), and large ($d>0.8$) effect (Sullivan & Feinn, 2012).

To investigate the roles of management types, habitats, and study design, we compared the basic pooled models with extended models that separately included the management type, habitats, study design, and their interactions with the treatment, separately for each variable. Models were compared by the likelihood ratio test. Significant differences between the basic and full models indicated that management type, habitats, or study design influenced the effect of pollinator-friendly management. Further analyses to differentiate between the influences of habitat and management types would be unreliable and

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potentially misleading, as the available datasets remain too limited and diverse for this purpose. Additionally, the pooled model's robustness was assessed by sensitivity analyses omitting each dataset in turn. We used the R statistical environment (v.4.4.3 RCoreTeam, 2025) packages glmmTMB (v.1.1.11 Brooks et al., 2017) and effsize (v.0.8.1 Torchiano, 2020).

RESULTS

Our data-based synthesis on pollinator-friendly management in protected areas integrated 34 primary datasets from 10 European countries that covered 1–5 sampling years, included 1–7 pollinator groups, and measured single or collective management impacts of abandonment, extensive mowing, extensive grazing, extensive mulching, and flower sowing in herbaceous vegetation and gap creation or uprooting and girdling in forests at 6–60 sites (Figure 1 & Appendix S2). Pooled analyses revealed significant positive effects of pollinator-friendly management on vegetation height ($p = 0.003$; Figure 2a) and abundance and species richness of other wild bees ($p = 0.002$, $p<0.001$; Figure 3b), butterflies ($p = 0.007$, $p<0.001$; Figure 3c), and total pollinators ($p = 0.016$, $p = 0.020$; Figure 4c & Appendix S4). However, after p-value adjustment, none of the significant differences changed, but many values were challenged by sensitivity analyses (Appendices S4 & S5). Based on Cohen's d, these management effects were small or negligible (Appendix S4). The pooled effects were never negative but were neutral for vegetation cover and abundance and species richness of flowers (Figure 2a,b), honey bees (Figure 2c), bumblebees (Figure 3a), hoverflies (Figure 4a), and beetles (Figure 4b & Appendix S4). Sensitivity analyses (Appendix S5) identified three influential datasets, altering statistical significance in seven instances (six from significant to nonsignificant [one dataset in each variable: flowers abundance, other wild bees abundance, other wild bees species richness, butterflies abundance, total pollinators abundance, total pollinators species richness] and one from nonsignificant to significant [one dataset in vegetation height]). Dataset-level analyses indicated 14.9% of the response, and dataset-level cases showed significant positive effects of pollinator-friendly management and 3.2% significant negative effects (Figures 2–4 & Appendix S6). Based on Cohen's d, significant positive treatment effects were large in 18 cases, medium in 10 cases, and small in five datasets, and significant negative treatment effects were large in one case, medium in two cases, and small in four cases (Appendix S6). The main effect of pollinator-friendly management was influenced by several drivers, as suggested by the relatively high importance of random factors (i.e., datasets, sites, sampling periods, and years; Appendices S4–S6), the likelihood ratio test-based model comparison between only treatment effect and full models (with management types, habitats, or study design; Appendix S7), and the extent of significant differences per response variable, management type, and habitat (Figures 2–4 & Appendix S8).

DISCUSSION

Our Europe-wide synthesis focusing on Central Europe showed that the impact of pollinator-friendly management in protected areas was mostly neutral, occasionally slightly positive, and never negative at the pooled level. However, at the dataset level, we found a few negative effects of pollinator-friendly management. Combining these results with those of the sensitivity analyses suggested that a few datasets with strong significant positive effects influenced the pooled-level results, and this finding also reinforced the neutral effects of management differences. The details behind any general patterns are important because pollinator guilds, habitats, and management types, as well as spatiotemporal dimensions, influence the effectiveness of management. Thus, to represent the needs of pollinators in protected areas, pollinator-friendly management plans must go beyond general patterns and be based on specific, local circumstances. For example, pollinator-friendly management increased the vegetation height in protected areas, most likely due to less intensive mowing or grazing. Allowing vegetation to grow may result in more flowers (Süle et al., 2023), benefiting flower-visiting insects and providing larval resources for butterflies (Smallidge & Leopold, 1997), as well as nesting opportunities for some cavity-nesting bees (Venn et al., 2023). However, tall, dense vegetation may be a disadvantage to ground-nesting species that require bare soil (Antoine & Forrest, 2021) and may cause microclimatic cooling (Wallisdevries & Van Swaay, 2006). In contrast, the floral resources in our synthesis did not show positive changes with pollinator-friendly management, which most likely occurred because established, well-functioning vegetation communities often found in protected areas cannot be rapidly or significantly altered through usual management changes, for example, only reducing mowing frequency. However, any initiated changes in other critical resources (e.g., nesting, overwintering, and larval) still benefit some pollinator groups, such as butterflies and wild bees (Hopfenmüller et al., 2020; Kőrösi et al., 2014).

Pollinator conservation in protected areas compared with in urban and agricultural areas

Management actions expected to increase pollinator abundance and richness in protected areas promoted butterflies and wild bees more than other pollinators, whereas the positive effect of these actions on the total number of pollinators was smaller. Responses of different pollinator taxa have been shown to vary by management intervention (Winfree et al., 2009) and landscape type (Dainese et al., 2017; Theodorou et al., 2020). For example, measures in agricultural ecosystems often promote bees, especially bumblebees (Maher et al., 2024; Söderman et al., 2016), whereas interventions in urban areas benefit both bumblebees and butterflies (Griffiths-Lee et al., 2022; Shwartz et al., 2013). Overall, based on existing literature, pollinator-friendly measures appear to be more effective in urban and

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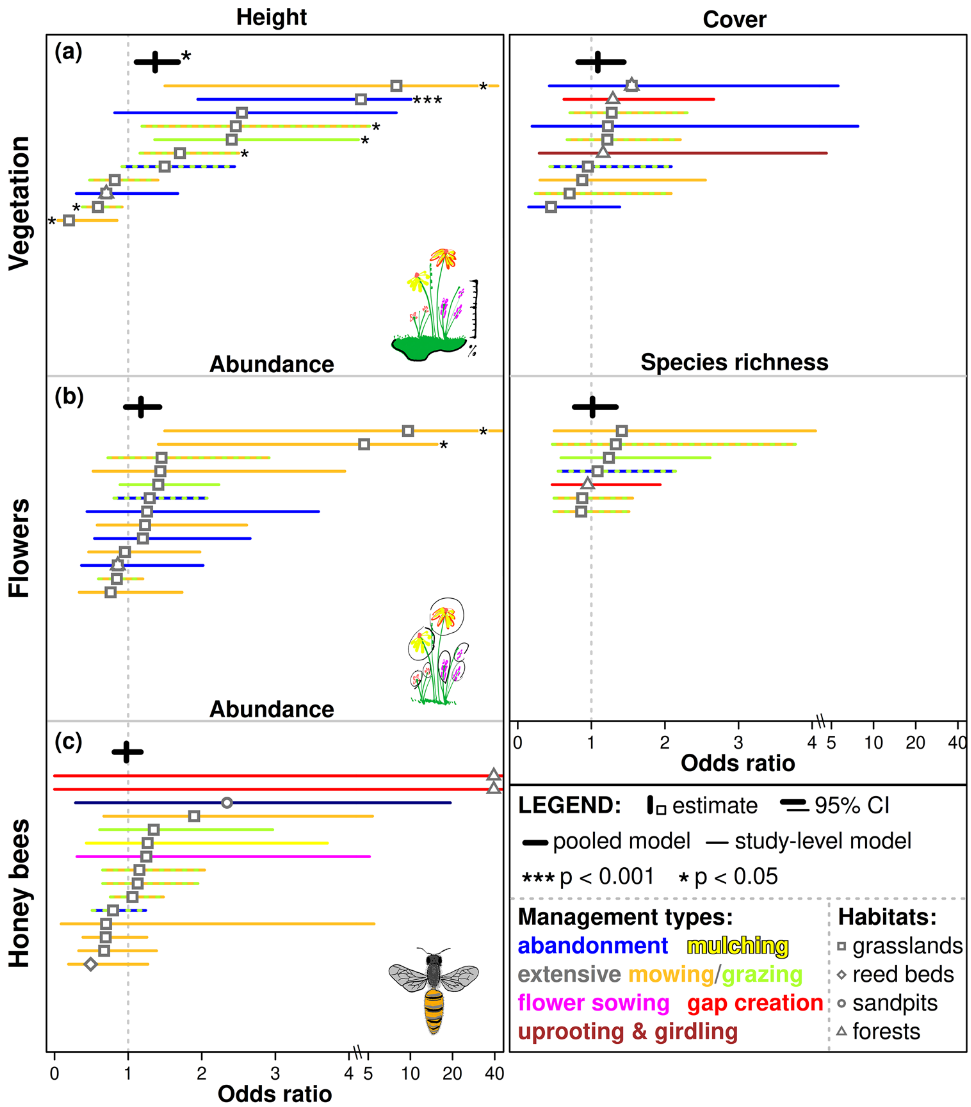

FIGURE 2 Impact of pollinator-friendly management on (a) vegetation height and cover; (b) flowers abundance and species richness; (c) honey bees abundance and keys of the colors, point, and line types. Odds ratio is the exponential of the model estimates and 95% confidence intervals. A value above one means a positive impact of pollinator-friendly management (treatment) compared with that of conventional management (control) in protected areas. The pooled models are presented with thick black lines, whereas dataset-level model estimations are presented with thinner, colorful lines and symbols. Stars indicate significant differences (* $p < 0.05$ and *** $p < 0.001$) on the corresponding side (as a positive or negative effect) of the lines. Double colors indicate more than one management type among the treatment sites in a dataset. X-axes change above value four to the log scale for better visualization. Outlier estimates are presented at the value of 40. Appendices S4 and S6 contain the exact model estimates, including the adjusted p values for the pooled models with the method of Benjamini and Hochberg (1995).

agricultural landscapes than in more natural protected areas (Millard et al., 2021; Süle et al., 2025; Theodorou et al., 2025). These differences most likely occur because actions on farmlands or in urban areas begin in a setting with fewer flowers and, thus, fewer pollinators as starting conditions. A novel intervention such as seeding wildflowers can swiftly change resource-poor sites into flower-rich habitats that benefit pollinators (Cariveau & Winfree, 2015; Kennedy et al., 2013), resulting in a significant ecological effect. This impact is mostly realized in the short term (Kleijn et al., 2011), but without careful habitat restoration, these areas could become ecological traps (i.e., attractive but maladaptive habitats) (Colla, 2022). Based on our results, forests in protected areas may also have only limited habitats for many pollinator species. Thus, gap creation and partial cutting can transform closed, flower-poor sites into sunlit woodland with flower-rich habitats (Kozel et al., 2021).

Site location and history may also influence the success of a pollinator-friendly management action, as larger and less fragmented protected areas in herbaceous habitats have vegetation types and conditions that already contain reasonable amounts of floral resources (Klinkovská et al., 2023), limiting large increases in local habitat conditions for pollinators. In contrast, small protected areas embedded in intensively managed agricultural landscapes may be insufficient for maintaining viable insect populations, as the effectiveness of management may be minimized by landscape-scale drivers (Hallmann et al.,

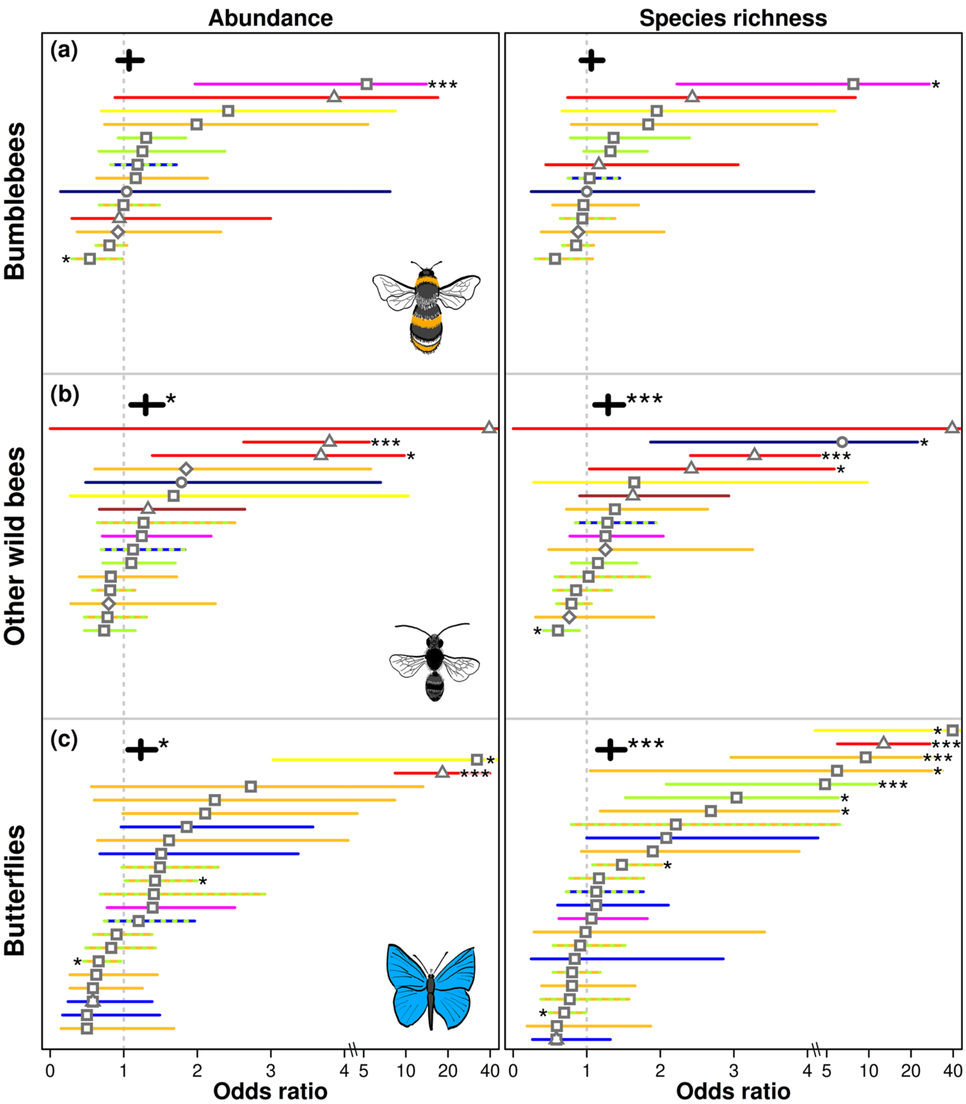

FIGURE 3 Impact of pollinator-friendly management on (a) bumblebees abundance and species richness; (b) other wild bees abundance and species richness; (c) butterflies abundance and species richness. For keys of the colors, point, and line types, please refer to Figure 2. Odds ratio is the exponential of the model estimates and 95% confidence intervals. A value above one means a positive impact of pollinator-friendly management (treatment) compared with that of conventional management (control) in protected areas. The pooled models are presented with thick black lines, whereas dataset-level model estimations are presented with thinner, colorful lines and symbols. Stars indicate significant differences (* $p < 0.05$ and *** $p < 0.001$) on the corresponding side (as a positive or negative effect) of the lines. Double colors indicate more than one management type among the treatment sites in a dataset. X-axes change above value four to the log scale for better visualization. Outlier estimates are presented at the value of 40. Appendices S4 and S6 contain the exact model estimates, including the adjusted p values for the pooled models with the method of Benjamini and Hochberg (1995).

2017). These issues are likely further compounded by the mostly generalist species found in agricultural and urban areas, as they may survive and disperse despite high disturbance levels, habitat loss, and fragmentation (Guariento et al., 2023; van Klink et al., 2024; Venn et al., 2023). Overall, the ecological impact of pollinator-friendly management tends to be greater in areas with lower-quality baseline conditions than in those with high-quality conditions (Marja et al., 2019; Scheper et al., 2013). Thus, even minor restoration efforts can increase local pollinator abundance in severely degraded habitats (i.e., cities and farmlands; Süle et al., 2025; Tscharntke et al., 2005). In contrast, maintaining intact or slightly degraded ecosystems (i.e., protected areas) can help rare and protected species, as well as yield greater biodiversity benefits over time (Kleijn et al., 2009). The neutral effects of pollinator-friendly management may indicate that protected area management is already meeting pollinator conservation goals. Moreover, the high sampling and dataset heterogeneity and synthesis-driven taxa pooling may also have contributed to these findings because each generalist, specialist, common, and rare species has specific resource and habitat requirements (Batáry et al., 2007; Thompson et al., 2021). As the requirements of these species are still relatively unknown (e.g., data deficiencies in the constantly developing IUCN Red Lists of butterflies [van Swaay et al., 2025] and wild bees [Michez et al., 2026]), it is

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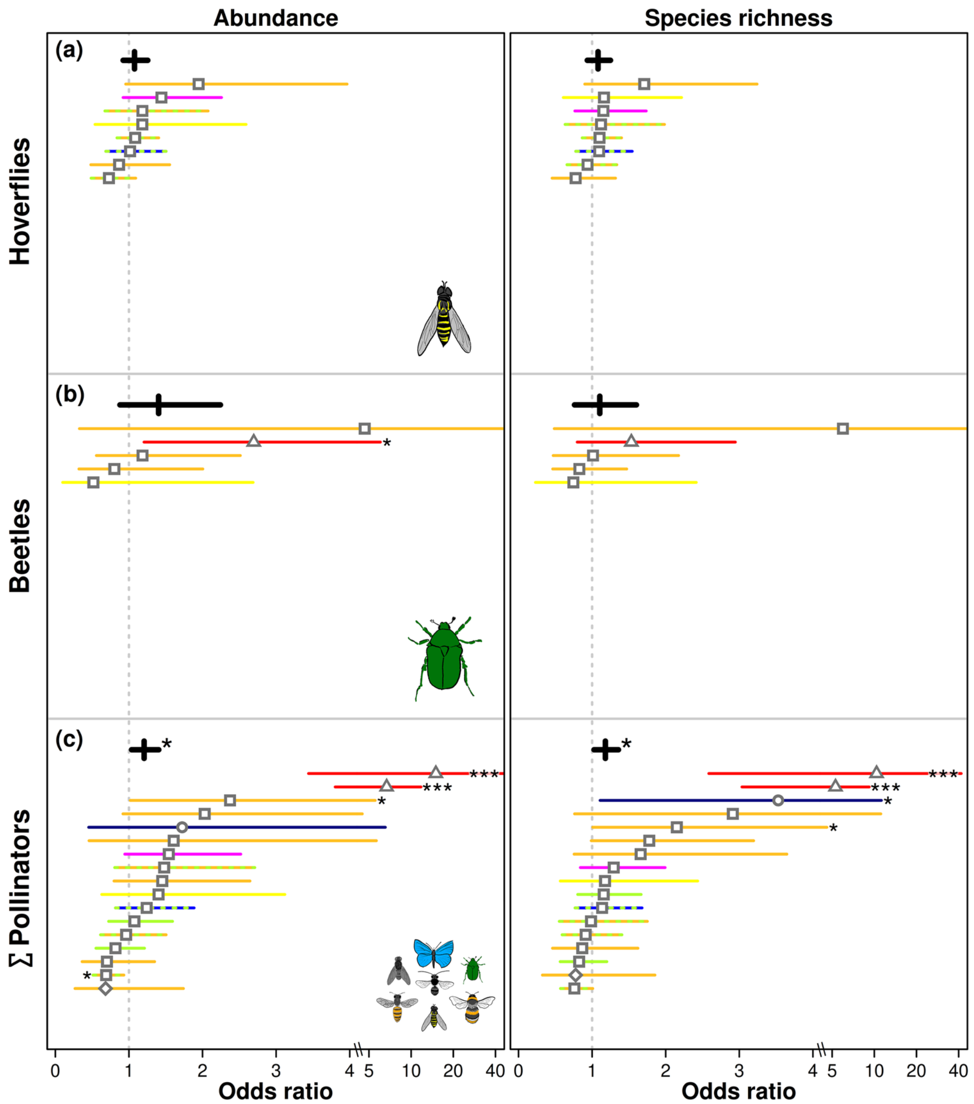

FIGURE 4 Impact of pollinator-friendly management on (a) hoverflies abundance and species richness; (b) beetles abundance and species richness; (c) total number of pollinators abundance and species richness. For keys of the colors, point, and line types, please refer to Figure 2. Odds ratio is the exponential of the model estimates and 95% confidence intervals. A value above one means a positive impact of pollinator-friendly management (treatment) compared with that of conventional management (control) in protected areas. The pooled models are presented with thick black lines, whereas dataset-level model estimations are presented with thinner, colorful lines and symbols. Stars indicate significant differences (* $p < 0.05$ and *** $p < 0.001$) on the corresponding side (as a positive or negative effect) of the lines. Double colors indicate more than one management type among the treatment sites in a dataset. X-axes change above value four to the log scale for better visualization. Outlier estimates are presented at the value of 40. Appendices S4 and S6 contain the exact model estimates, including the adjusted p values for the pooled models with the method of Benjamini and Hochberg (1995).

also possible that different species' responses to the same management may counteract one another. Consequently, pooled analyses may mask important species-level effects, representing limitations to global and even continental-level generalizations for pollinator conservation.

In addition to these explanations for the neutral impacts of pollinator-friendly management actions in protected areas, the high-quality baseline conditions of protected areas may also mean that current conservation management cannot further enhance the habitat for pollinators. Compared with field experiments in agricultural and urban systems, those in protected areas have not involved substantial management changes, limiting the evaluation and development of effective management practices in these areas. However, seminatural habitats have been subjected to a gradient of management intensities over centuries; thus, studying the past and present impacts of management on pollinators in these areas may provide some insights (Biró et al., 2024). Limited available evidence about the management age and year effect also constrains pollinator research (Süle et al., 2025). However, recently restored habitats can serve as field experimental systems for testing the effects of different management actions (e.g., conservation-focused living laboratories), but only within long-term frameworks (Winfree et al., 2009). Field experiments (including control-treatment approaches) in

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protected habitats are also hampered by several factors, including legal restrictions and spatial extent, which is generally larger than the borders of parks or the margins of agricultural parcels. Similarly, these habitats and their conservation must accommodate the needs of multiple species rather than focusing on specific ecosystem service providers, such as pollinators, which can be accommodated in agrienvironmental systems (Báldi et al., 2013; ECA, 2020). Additionally, the majority of the datasets used in our synthesis were from Central Europe, and these data differ from those in agricultural and urban studies that have been conducted primarily in Northwestern Europe (Albrecht et al., 2020; Süle et al., 2025). These spatial differences possibly explain some of the results because climate and anthropogenic impacts on local habitat type, size, quality, and management and landscape history, heterogeneity, and fragmentation differ across Europe (Batáry et al., 2010; Biró et al., 2024; Csákvári et al., 2021).

Our Europe-wide comparison of management approaches in protected areas demonstrated that management actions in protected areas need to be more specific than those applied in agricultural and urban settings. In protected areas, pollinator habitat management depends on local habitat type, historical context, and target taxa. Therefore, given our collective expertise in pollinator ecology, we offer recommendations about protected area management.

Management actions

One of our initial objectives was to separate the effects of habitat type and management type on pollinator abundance and richness. Despite limited data on certain types of habitats (e.g., sand pits and forests) and management (e.g., flower sowing), apparent differences indicated that habitat characteristics, management practices, and their interactions may influence the condition of protected areas (Figures 2–4). For example, the characteristics of grasslands are linked to a range of outcomes from different management actions (Torma et al., 2023). Complete abandonment of a grassland enables successional processes to occur and can facilitate the spread of invasive nonnative plants, which can be detrimental to pollinators (Ernst et al., 2017; Murray et al., 2012; Szigeti et al., 2023). Thus, most grassland habitats need some mowing or grazing to preserve biodiversity (Fumy & Fartmann, 2023; Poniatowski et al., 2018). Intensity and timeframe of management, mowing methods, and grazing types are also crucial factors (Mora et al., 2022) because they influence nutrient accumulation, phytodiversity, and blooming (Liu et al. 2015; Georgi et al., 2023). Furthermore, according to the wood-pasture hypothesis, reintroducing large herbivores would naturally restore open woodlands and intermediate disturbances, supporting habitats for pollinators (Garrido et al., 2019). This range of grassland management needs highlights that protected area habitats require more attentive, meticulous, and locally designed long-term management plans.

Natural and human-induced disturbances, such as floods, fires, and grazing, modify habitats and open empty niches and are important factors in managing pollinator habitat in protected areas (Bogusch et al., 2015; Cappellari & Marini, 2021; Potts et al., 2005). Although some disturbance is essential to preserve natural processes, for centuries, humans have attempted to control or regulate these processes by influencing timing and frequency. Some disturbances, such as fires and floods, have been suppressed or banned in Europe (Valkó et al., 2014), but prescribed burns continue to be used in conservation strategies in the United States (Glenny et al., 2022) and heathlands in Europe (Mohamed et al., 2007). Most likely, natural plant–pollinator systems in Europe have adapted to moderate levels of a mosaic of biotic and abiotic disturbances. However, there are two concerning trends in habitat management that can affect disturbance regimes: many disturbances have become more uniform and intense (e.g., large tractors that mow too quickly), especially in Northwestern Europe, whereas traditional, extensive land management practices have disappeared, resulting in complete land abandonment (Fumy & Fartmann, 2023) that transforms grasslands into forests in Central-Eastern Europe (Mora et al., 2022). Therefore, European biodiversity may benefit from the reintroduction of intermediate-level disturbances (Fox, 2013; Roxburgh et al., 2004) given the nonlinear interrelations between spatiotemporal heterogeneity (i.e., structural complexity of habitats) and species' traits (e.g., insects' mobility; Gao & Carmel, 2020; Winfree et al., 2009).

This broader perspective is where targeted management can help. For instance, timing and spatial adjustments such as mosaic mowing (Parmentier et al., 2024), rotational and low-intensity grazing (Farruggia et al., 2012), or refuge strips (Révész et al., 2025) could support pollinator diversity by creating heterogeneous vegetation structures with hiding places, nesting sites, and food resources (Parmentier et al., 2024; Schwarz et al., 2023). Mulching, which involves shredding cut vegetation and leaving it in place, can be controversial because while it helps spread plant species' seeds, it may reduce phytodiversity through nutrient enrichment over time (Georgi et al., 2023). However, experimenting with different types of sustained or temporal disturbances could be beneficial for conservation and ecology (Cook et al., 2013; Glenny et al., 2022).

Other restoration approaches in protected seminatural habitats (e.g., old fallows, disturbed secondary grassland, and forest clear-cuts) should be carefully considered. For example, flower sowing, a highly beneficial practice in cities and farmlands (Albrecht et al., 2020; Süle et al., 2025), is rarely authorized and studied in seminatural habitats. The lack of native seeds and local laws pose additional challenges to the practice of overseeding degraded protected habitats (Bihaly et al., 2024; Mainz & Wieden, 2019). From a conservation perspective, any intensive intervention should be thoroughly justified, beginning with the genetic and functional diversity of the sown seeds, progressing to the establishment of long-term maintenance, funding schemes, and adequate monitoring and feedback systems (Goret et al., 2021).

Pollinator-friendly management actions differ by habitat type, with grasslands receiving the greatest attention in the literature; however, forests have untapped potential for pollinators through habitat enhancement (Eckerter et al., 2021). In our

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study, pollinator-friendly management actions resulted in positive impacts on floral resources and pollinators in forests, indicating that there is a lack of floral resources in conventionally managed woodlands with dense, mid-successional phases relative to those in open woodlands and forest–grassland mosaics with more ecotones that the gap creations resemble (Erdős et al., 2018; Sinclair et al., 2025). Management actions to enhance forests for pollinators include facilitating canopy openings that could create local niches for pollinators with light, flowers, and nesting opportunities (Fartmann et al., 2013; Kozel et al., 2021). Maintaining all forest successional stages, including unmanaged sites, small clear-cuts, and open forest edges with herbaceous vegetation, could increase the resilience of pollinator communities by enhanced landscape-scale resources and microclimatic heterogeneity (Eckerter et al., 2022; Weiss et al., 2021).

Understudied habitat types, such as sandpits and reed beds, may play an essential role in providing nesting sites for cavity- and ground-nesting species (Heneberg et al., 2013, 2017). Pollinators can benefit from habitat management even when floral resources remain unchanged, indicating that other limiting factors, such as nesting or larval resources, are at work (Albrecht et al., 2023; Requier & Leonhardt, 2020). Thus, improving and monitoring all potential resources for pollinators are important and should be complemented by investigating management-driven environmental factors, from vegetation height to nitrogen deposition, that affect them (Settele et al., 2024; Theodorou et al., 2025). Finally, it is important to recognize that not all pollinator-friendly strategies work on the same timescale in all types of landscapes and habitats due to site size, vegetation type, successional phase, historical land use, resource availability, matrix quality (e.g., landscape fragmentation), and local climatic and socioecological circumstances (Duffus et al., 2025). These factors highlight the importance of local conservation planning (Pellaton et al., 2023). Similarly, further studies should investigate wider habitat networks and consider a protected area's size, historical context, landscape characteristics, and type and intensity of habitat management. Thus, holistic approaches will ensure that conservation actions consider these important factors. Although knowledge of historical pollinator diversity remains limited, conservation should target baseline ecological conditions through restoration (Millard et al., 2021).

Additional considerations for pollinator conservation

Even if appropriate management is established, a key question remains: should we prioritize preserving seminatural ecosystems or restoring degraded habitats? In degraded landscapes, small, remaining, but mostly disturbed habitat patches often attract pollinators with their rich floral resources (Theodorou et al., 2025). In contrast, natural habitats sustain significantly higher amounts of biodiversity over time due to long-term maintenance; thus, many feel they should be prioritized for conservation. Outside of these two points, comparing anthropogenic and natural landscapes is a complex topic. Protected areas provide suitable habitats for pollinators across their entire extent, whereas urban and agricultural landscapes include large unsuitable areas for pollinators (e.g., plowed or built-up land), with limited seminatural patches. Thus, potential sources of bias occur when field studies sample and compare only isolated habitat patches in the short term rather than studying the whole landscape over the long term (Fijen et al., 2025; Kleijn et al., 2018). As most pollinator populations require spatially appropriate habitat to survive, farmlands and cities inherently sustain lower biodiversity than landscapes of the same extent with many seminatural sites, such as protected areas. Still, in intensive agricultural regions (e.g., Western Europe), urban habitats can be biodiversity hotspots (Baldock et al., 2015). Although the emerging EU pollinator monitoring program will hopefully address these aspects (Settele et al., 2024), both anthropogenic and natural habitats offer significant opportunities for restoration. Therefore, the answer to the question above is not to prioritize a single landscape or habitat type but rather to promote and monitor pollinators across agricultural, urban, and protected landscapes with adapted approaches.

Importantly, pollinator conservation is often too little and too late and occasionally misses the appropriate focus (Drivdal & van der Sluijs, 2021). Only a few protected areas are designated specifically for insects (mainly butterflies), and they often ignore the requirements of most pollinators, perhaps because managers assume pollinators already benefit from general biodiversity-focused management (Chowdhury et al., 2023). Our synthesis lacks full geographical coverage, taxonomic completeness, and uniformity in the sampling or study design, limiting the generalizability of currently available knowledge. However, without efforts to gather robust scientific evidence, all statements remain speculative, thereby hindering the implementation of effective policies. For example, different levels of nature protection (e.g., nature reserves, Natura 2000 network, and nature restoration regulation) can lead to different outcomes, owing primarily to a lack of targeted habitat management (Dudley, 2008; European Commission, 2025). Legal protections and their implementation vary globally and within the EU (European Environment Agency, 2025). The designation and management of protected sites do not have uniform definitions and impacts, despite previous efforts toward EU-level coordination (European Parliament, 2024). Overall, this situation reflects a substantial lack of consistency in conservation practice across the continent. Despite increased awareness, ecological studies evaluating the efficiency of protected areas, particularly management actions, remain scarce (Glenny et al., 2022; Theodorou et al., 2025).

The desired expansion of European protected areas will require targeted conservation strategies that foster collaboration among the stakeholders (e.g., herders and national park rangers) managing various habitat types (CBD, 2022; Ratamäki et al., 2015). For pollinators, such an endeavor necessitates defining their current habitat conditions and optimal restoration and maintenance approaches (Chowdhury et al., 2023), which require traditional and local knowledge (Moller et al., 2004) combined with novel scientific and policy efforts (Hall & Steiner, 2019; Theodorou et al., 2025). Pollinator-friendly

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actions in protected areas should be evidence-based, consider local conditions, and use stakeholder feedback systems (Fazey et al., 2014; Reyes-García et al., 2019). In addition, the European Nature Restoration Regulation's focus on pollinators can serve as the basis to reconsider and revise unsustainable and counterproductive laws and policies for habitat management (e.g., mowing schedules that do not consider weather impacts) to ensure they benefit to ecosystems (Sucholas et al., 2025).

Protected areas are essential for pollinator survival, and because there are increasing demands for ecosystem services in degraded landscapes, management strategies aligned with conservation goals to maintain natural habitats as refuges for rare and threatened species must also be implemented. Although most management actions may benefit pollinators, our results showed that pollinator-friendly management was less beneficial than expected in Central European protected areas. Although our synthesis was focused and designed for Europe, the potential effects of pollinator-friendly management varied among regions. Thus, the broader habitat management recommendations, main themes, knowledge gaps, and limitations are applicable worldwide, but only after careful adaptation to local socioeconomic and ecological conditions. Finally, it is time to focus on pollinators, among multiple other taxa, in protected habitat, through detailed studies and enhanced conservation strategies. Effective pollinator conservation should involve more novel and innovative strategies, legislative changes, large-scale experimental systems, long-term monitoring, and targeted nationally and internationally funded projects, especially for protected areas. The next step for pollinator-focused conservation research should be a global meta-analysis of pollinator-friendly management approaches simultaneously examined in agricultural, urban, and protected landscapes.

ACKNOWLEDGEMENTS

We are thankful to A. Dronova (Estonia), L. Ernst (Germany), and F. Kőhalmi, B. Kovács, A. Máté, and D. Teplánszki (Hungary) for collecting and sorting the datasets and to Z. Botta-Dukát for conceptualizing the analyses. This study received funding from the European Union's Horizon 2020, No. 101003476 Safeguard: Safeguarding European wild pollinators (https://www.safeguard.biozentrum.uni-wuerzburg.de).

The authors and owners of the primary datasets were supported by broad funding sources:

A.B.: Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA);

T.E., F.F., and F.L.: Deutsche Bundesstiftung Umwelt (DBU);

T.E. and G.M.: gemeinnützige Verlagsgesellschaft mbH (FAZIT-Stiftung);

E.G. and A.H.: Biodiversity Monitoring South Tyrol project by Autonomous Province of Bolzano/Bozen;

J.H. and K.N.: Specific project PřF UHK 2101/2024;

R.I.H. and T. Frank: Austrian Academy of Sciences (project: Healthy Alps, project number: 10470);

A.M.K.: European Union's Horizon Europe No. 101082101 "RestPoll" project;

P. Bogusch: Excellence Project of PřF UHK 2202/2025;

G.M.: Landesgraduiertenförderug (LGFG); and

C.T. (NKFIH K 146137) and V.S. (STARTING 150181) by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund.

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How to cite this article: Süle, G., Báldi, A., Kleijn, D., Steffan-Dewenter, I., Albrecht, M., Batáry, P., Biegerl, C., Bogusch, P., Braunisch, V., Buse, J., Cappellari, A., Eckerter, T., Fartmann, T., Frank, T., Fumy, F., Garratt, M., Georgi, M., Guariento, E., Heneberg, P., … Szigeti, V. (2026). Synthesis of Pollinator-Friendly Management in European Protected Areas. *Conservation Biology*, e70366. https://doi.org/10.1111/cobi.70366

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