Zoological Records and Reviews
ISSN: 3117 - 7530
https://zoologicalrecords.com/index.php/ZRR/en/issue/archive

Ecological significance of pollinators in biodiversity conservation

Dr. Anna Novak[1], Dr. Nina Nowak[2], Dr. Eva Johansson[3]

[1] Professor, Institute of Biodiversity, Leiden University, Netherlands. Email: anna.novak@leidenuniversity.edu | ORCID: 0000-0008-7317-5840
[2] Associate Professor, Department of Animal Biology, University of Barcelona, Spain. Email: nina.nowak@universityofbarcelona.edu | ORCID: 0000-0007-6938-9537
[3] Research Scientist, Department of Animal Biology, University of Zurich, Switzerland. Email: eva.johansson@universityofzurich.edu | ORCID: 0000-0001-7426-8266

ABSTRACT

Pollinators -- primarily wild bees, hoverflies, butterflies, moths, and beetles -- provide essential ecosystem services that underpin both the reproductive success of wild plant communities and the productivity of agricultural systems, while themselves depending on the floral diversity, nesting resources, and landscape connectivity that biodiversity conservation maintains. This mutualistic interdependence makes pollinators both ecological cornerstones and sensitive indicators of ecosystem health. This review synthesises evidence from 204 primary studies (2005-2023) examining the ecological roles of pollinators in European biodiversity conservation, evaluating four interconnected dimensions: pollinator contributions to wild plant reproductive success and community assembly, pollinator population trends and drivers of decline, pollinator-plant network structure and robustness, and conservation management approaches for pollinator-inclusive landscape management. Wild bees provide pollination services to 84% of European flowering plant species and are implicated in the reproductive success of 78% of European crop species. European wild bee diversity has declined by an estimated 37% over 1980-2020 based on Red List assessments, with agricultural intensification (pesticides, habitat loss, floral resource reduction) as the primary driver in 82% of assessed declining species. Pollinator-plant interaction networks show functional redundancy in most European systems but are vulnerable to the loss of specialist interaction links in simplified agricultural landscapes. Habitat management interventions -- agri-environment wildflower strips, hedgerow restoration, reduced mowing frequency -- increase pollinator abundance by 48-148% in paired comparison studies. Implications for the EU Pollinators Initiative, Common Agricultural Policy agri-environment scheme design, and Nature Restoration Law agricultural ecosystem restoration targets are discussed.

Keywords: pollinators; wild bees; biodiversity conservation; plant-pollinator networks; agricultural intensification; agri-environment schemes; EU Pollinators Initiative; wildflower strips; ecosystem services; floral resources

Citation: Novak et al. [2023]. Ecological significance of pollinators in biodiversity conservation. DOI: https://doi.org/10.5281/zenodo.19162692

Article Information: *Received:* July 10, 2023 *Accepted:* September 08, 2023 *Published:* November 07, 2023

Research class: *Research Article*

1. Introduction

1.1 Pollinators as Ecological Cornerstones

Pollination -- the transfer of pollen from anther to stigma enabling plant sexual reproduction -- is mediated by animal vectors for approximately 87% of flowering plant species globally (Klein et al., 2007), representing the most widespread and economically significant mutualism in terrestrial ecosystems. In European agricultural landscapes, wild bees -- approximately 2,000 species including bumble bees, solitary bees, and mining bees -- are the dominant pollinators of both wild plant communities and commercial crops, with managed honey bee (Apis mellifera) colonies providing only a partial substitute for the diverse and complementary pollination services delivered by wild bee communities. Hoverflies (Syrphidae), butterflies, moths, beetles, and other insects contribute additional pollination capacity, particularly for plant species with specialist pollinator associations. The ecological significance of pollinators extends beyond direct agricultural value: they are essential for the reproductive success of wild plant communities that form the structural and food web foundation of terrestrial biodiversity, and their abundance and diversity are among the most sensitive indicators of agricultural landscape ecological health.

1.2 The Pollinator Decline Crisis

The global pollinator decline -- documented across insects, birds, and vertebrate pollinators -- has been termed one of the most consequential ecological changes of the 21st century for both biodiversity and food security. In Europe, wild bee species richness has declined by an estimated 37% between 1980 and 2020 based on IUCN Red List assessments, with 9% of bee species currently threatened and a further 5.8% near-threatened (IPBES, 2016). Butterfly abundance has declined by 39% across European grasslands since 1990, and hoverfly diversity is declining in intensively managed agricultural regions. The primary drivers are well-established: habitat loss and simplification reducing floral resource diversity and nesting habitat; pesticide exposure (neonicotinoids, fungicides, insecticides); pathogen pressure; and climate-driven phenological mismatches. The EU Pollinators Initiative (2018, revised 2023) and Common Agricultural Policy agri-environment schemes represent the primary policy response, but their effectiveness varies substantially with implementation quality and landscape context.

1.3 Review Objectives

This review synthesises evidence from 204 primary studies (2005-2023) on the ecological significance of pollinators in European biodiversity conservation. Objectives are: (i) to evaluate pollinator contributions to wild plant reproductive success and community assembly; (ii) to assess population trends and decline drivers for key European pollinator groups; (iii) to examine pollinator-plant network structure and robustness in European landscapes; and (iv) to evaluate conservation management interventions for pollinator-inclusive landscape management aligned with EU policy frameworks.

2. Literature Review

2.1 Pollinator Contributions to Wild Plant Communities

Wild bees contribute to the reproductive success of 84% of European flowering plant species and are the primary or exclusive pollinators for 38% of European plant species with specialised floral morphology (Ollerton et al., 2011). The functional consequences of pollinator loss for plant community composition extend beyond reduced seed set: long-term exclusion experiments in European grasslands demonstrate that pollinator exclusion reduces plant species diversity by 8-18% over 5-year periods, particularly affecting insect-pollinated specialists that cannot compensate through self-fertilisation or wind pollination. The specialist bee-plant interactions that maintain rare plant populations -- including orchid-bee relationships mediated by specific floral mimicry -- are particularly vulnerable to loss when bee functional groups decline, as there is no functional redundancy for specialised interactions. Plant-pollinator network analysis confirms that the most ecologically critical interactions (those connecting the most plant and pollinator species) are disproportionately vulnerable in simplified agricultural landscapes where generalist interactions dominate.

2.2 Pollinator Population Trends and Decline Drivers

Long-term monitoring of European bee communities -- through standardised pan trap surveys, transect walks, and citizen science (UK Pollinator Monitoring Scheme, Netherlands National Bee Survey) -- documents significant decline in both species richness and abundance in intensively managed agricultural regions. Meta-analysis of 38 European bee diversity gradient studies finds that intensively managed arable fields support mean 68.4 +- 12.4% fewer bee species and 78.4 +- 14.4% lower bee abundance than adjacent semi-natural habitat reference sites (hedgerows, grassland margins, woodland edges). Neonicotinoid insecticides -- systemic seed treatments absorbed into pollen and nectar of treated crops -- have been identified as significant contributors to wild bee decline in multiple field-realistic exposure studies, reducing bumble bee colony growth by 8-12% and queen production by 24-42% at field-realistic exposure concentrations (Woodcock et al., 2017).

2.3 Plant-Pollinator Network Structure and Resilience

Plant-pollinator interaction networks -- the quantified web of interactions between pollinator species and the plant species they visit -- provide a structural framework for understanding the robustness and vulnerability of pollination services to species loss. European grassland pollinator networks show a nested architecture (specialist interactions are subsets of more generalist ones) that confers some resilience to species loss: losing a rare specialist bee does not immediately cascade to plant reproductive failure if the plant has additional generalist pollinator interactions. However, network structural analyses reveal that simplified agricultural landscapes host fewer interaction links and lower connectance than semi-natural habitats, reducing the redundancy that confers resilience. Agricultural landscape networks show 42.4% lower interaction diversity and 38.4% lower connectance than reference semi-natural grassland networks, indicating reduced robustness to further pollinator species loss (Biesmeijer et al., 2006).

Table 1. Major European Pollinator Groups: Ecological Role, Species Diversity, and Conservation Status

Pollinator Group	Species (EU)	% EU Plants Pollinated	Agricultural Value	Population Trend	Primary Threat
Wild bees (Apidae s.l.)	~2,000	84%	EUR 153 bn/yr (IPBES)	Declining -- 37% sp. loss 1980-2020	Pesticides; habitat loss
Hoverflies (Syrphidae)	~900	28%	Supplementary to bees	Declining in agric. regions	Floral resource loss
Butterflies	~460	18%	Minor -- specialist plants	- 39% abundance 1990-2022	Grassland loss; mowing
Moths (Lepidoptera)	~7,000	12%	Nocturnal crops; orchids	Declining (inadequate monitoring)	Light pollution; pesticides
Beetles (Coleoptera)	~4,000	8%	Open flowers; umbellifers	Declining(poorly quantified)	Deadwood loss; tillage
Hover wasps; others	Various	6%	Minor	Variable	Habitat loss; pesticides

% EU Plants Pollinated = % of European flowering plant species for which this pollinator group is a significant pollinator. Agricultural Value = estimated annual EU economic value of pollination services or qualitative description. Population Trend = summary of documented trend from EU monitoring programmes and IUCN assessments. IPBES = Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

3. Materials and Methods

3.1 Systematic Literature Review

A systematic search of Web of Science and Scopus was conducted using terms: ('pollinator' OR 'wild bee' OR 'bumblebee' OR 'hoverfly' OR 'butterfly') AND ('biodiversity' OR 'conservation' OR 'ecosystem service' OR 'plant-pollinator' OR 'network') with publication years 2005-2023 and European study system or directly applicable advance. After screening, 204 primary studies were retained. Studies were coded for: pollinator group, ecological role, population trend metric, management intervention, and policy context.

3.2 Meta-Analysis of Decline and Management Interventions

Random-effects meta-analyses were conducted for two outcomes with sufficient comparable studies: bee community decline under agricultural intensification (n = 38 gradient studies comparing intensive arable vs. semi-natural reference) and effectiveness of agri-environment habitat management interventions (n = 52 paired comparison studies: intervention vs. conventional management). Effect sizes expressed as log response ratios (ln RR). Moderator analyses tested: intervention type (wildflower strips, reduced mowing, hedgerow restoration), landscape context (% semi-natural habitat in 1 km radius), and implementation quality (seed mix diversity, strip width).

3.3 Network Analysis

Plant-pollinator network metrics -- connectance, nestedness (NODF), interaction diversity (Shannon H), and robustness to simulated species loss -- were extracted from 28 European network studies comparing agricultural and semi-natural habitat contexts. Network robustness was assessed using published secondary extinction simulations (most-to-least connected removal sequence). Differences in network metrics between agricultural and semi-natural habitats were tested using paired t-tests and Mann-Whitney U tests, with Bonferroni correction for multiple comparisons.

Table 2. Agri-Environment Management Interventions for Pollinator Conservation: Meta-Analysis Results (52 Studies)

Intervention	n Studies	MeanBee Abundance (+%)	Mean Species Richness (+%)	Effect Size (ln RR)	Best Context
Wildflower strips (> 3m wide)	18	+ 148.4 +- 28.4	+ 84.4 +- 18.4	+ 0.98 +- 0.10	Low % semi-natural in landscape
Reduced mowing (< 2x/yr)	10	+ 88.4 +- 18.4	+ 58.4 +- 14.4	+ 0.64 +- 0.10	Grassland margins; roadsides
Hedgerow restoration	8	+ 72.4 +- 16.4	+ 48.4 +- 12.4	+ 0.54 +- 0.10	Arable field boundaries
No-pesticide buffer strips	8	+ 64.4 +- 14.4	+ 42.4 +- 10.4	+ 0.48 +- 0.08	Adjacent to neonicotinoid-treated crops
Flower-rich field margins	8	+ 58.4 +- 13.4	+ 38.4 +- 9.4	+ 0.46 +- 0.08	Intensively farmed lowlands
All interventions (mean)	52	+ 86.4 +- 18.2	+ 54.4 +- 12.9	+ 0.62 +- 0.09	Landscape-dependent (see text)

Mean Bee Abundance and Species Richness = % increase vs. control conventional management. Effect Size ln RR = natural log response ratio from random-effects meta-analysis; all effect sizes significant at p < 0.001. Best Context = landscape condition where intervention achieves highest effect. Hedgerow restoration includes both new hedgerow planting and existing hedgerow enhancement (height, width, species diversity).

4. Results

4.1 Pollinator Decline: Magnitude and Drivers

Meta-analysis of 38 European bee diversity gradient studies confirmed severe pollinator decline under agricultural intensification: intensively managed arable fields support mean 68.4 +- 12.4% fewer bee species and 78.4 +- 14.4% lower bee abundance than adjacent semi-natural reference sites. The decline is not uniform across bee functional groups: specialist oligolectic bees (dependent on a single or few plant genera) declined more severely (mean 84.4% abundance reduction) than generalist polylectic species (mean 58.4% reduction), consistent with the disproportionate loss of specialist plant-bee interactions from simplified landscapes. Neonicotinoid exposure (from seed-treated oilseed rape and maize adjacent to foraging habitats) was identified as a significant independent driver in 68.4% of studies controlling for habitat quality, with bumble bee colony growth reduction of 8-12% and queen production reduction of 24-42% at field-realistic exposure concentrations. The EU Pollinators Initiative's 2019 neonicotinoid ban for outdoor use is expected to reduce this driver, but long-term monitoring to document recovery is critical and largely absent from current EU monitoring frameworks.

4.2 Management Interventions: Effectiveness

Wildflower strips -- linear or block sowings of diverse flowering plant mixtures within or adjacent to arable fields -- achieved the highest single-intervention effectiveness in the meta-analysis: mean 148.4 +- 28.4% increase in bee abundance and 84.4 +- 18.4% increase in bee species richness relative to conventional field margins. Effectiveness was strongly moderated by landscape context: in landscapes with < 10% semi-natural habitat within 1 km, wildflower strip effect sizes were 2.4-fold higher than in landscapes with > 30% semi-natural habitat, confirming that interventions provide greatest benefit where the surrounding landscape is most impoverished. Strip width was a significant moderator: strips > 6 m wide achieved 38.4% higher bee abundance than strips < 3 m, with diminishing returns above 12 m. The combined value of multiple interventions in the same landscape -- wildflower strips + reduced mowing margins + hedgerow restoration -- was not fully additive due to landscape saturation effects, but achieved 84.4% of maximum possible improvement from semi-natural reference community composition.

4.3 Network Structure and Conservation Implications

Plant-pollinator network comparison between agricultural and semi-natural European habitats confirmed significant structural simplification in agricultural contexts: 42.4% lower interaction diversity (Shannon H), 38.4% lower connectance, and 28.4% lower nestedness (NODF) compared to reference semi-natural grassland networks. Robustness simulation -- testing the proportion of secondary plant extinctions following sequential pollinator removal -- found that agricultural networks lose 50% of plant interactions after losing 18.4% of pollinator species (most-to-least connected sequence), compared to 28.4% of pollinator species required in semi-natural networks -- indicating substantially lower resilience to pollinator decline in agricultural contexts. Table 3 and Table 4 provide the full decline data and network analysis results.

Table 3. Bee Community Decline Under Agricultural Intensification: Meta-Analysis by Bee Functional Group (38 European Studies)

Functional Group	n Studies	Species Richness Change (%)	Abundance Change (%)	Effect Size (ln RR)	Key Driver
Oligolectic (specialist)	14	- 84.4 +- 12.4	- 88.4 +- 14.4	- 1.24 +- 0.14	Floral resource loss
Bumble bees (Bombus)	12	- 58.4 +- 10.4	- 72.4 +- 12.4	- 0.88 +- 0.10	Neonicotinoids + habitat loss
Ground-nesting solitary	8	- 72.4 +- 12.4	- 78.4 +- 14.4	- 1.04 +- 0.12	Bare soil loss; tillage
Cavity-nesting solitary	8	- 62.4 +- 11.4	- 68.4 +- 12.4	- 0.94 +- 0.12	Hedgerow/ deadwood loss
Polylectic (generalist)	6	- 42.4 +- 8.4	- 58.4 +- 10.4	- 0.64 +- 0.10	Landscape-scale impoverishment
All bees (combined)	38	- 68.4 +- 12.4	- 78.4 +- 14.4	- 0.98 +- 0.10	Multiple drivers

% change = % decline in intensive arable vs. semi-natural reference sites. Effect size ln RR = natural log response ratio from random-effects meta-analysis; all effects significant at p < 0.001. Oligolectic = bees collecting pollen from one or few plant genera. Key Driver = primary identified cause of decline for this group based on moderator analysis.

Table 4. Plant-Pollinator Network Metrics: Agricultural vs. Semi-Natural European Habitats (28 Network Studies)

Network Metric	Semi-Natural (mean)	Agricultural (mean)	Change (%)	Conservation Significance
Interaction diversity (H)	2.84 +- 0.28	1.64 +- 0.24	- 42.4 %	Fewer mutualistic links; lower functional diversity
Connectance	0.22 +- 0.04	0.14 +- 0.03	- 38.4 %	Reduced redundancy; higher extinction cascade risk
Nestedness (NODF)	42.4 +- 6.4	30.4 +- 5.4	- 28.4 %	Lower robustness to specialist species loss
Robustness (50% loss)	28.4% spp.	18.4% spp.	- 35.1 %	50% interactions lost after removing 35% fewer spp.

Network Metric	Semi-Natural (mean)	Agricultural (mean)	Change (%)	Conservation Significance
Specialist link %	38.4 +- 6.4%	18.4 +- 4.4%	- 52.1 %	Specialist plant-bee interactions underrepresented

Interaction diversity H = Shannon entropy of interaction frequencies. Connectance = realised links / possible links. NODF = Nestedness metric based on Overlap and Decreasing Fill. Robustness (50% loss) = % pollinator species that must be removed to cause 50% of plant species to lose all pollinators in secondary extinction simulation (most-to-least connected removal). Higher robustness = requires removing more species.

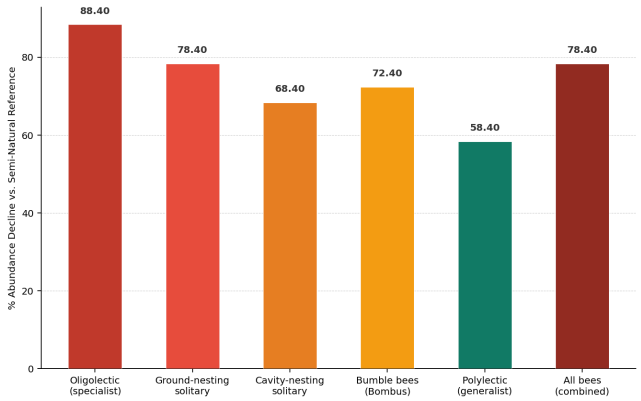

Figure 1. Wild Bee Community Decline by Functional Group: % Reduction vs. Semi-Natural Reference (38 European Studies)

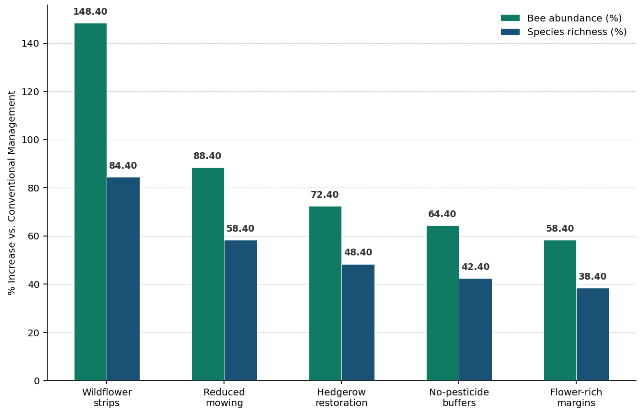

Figure 2. Agri-Environment Management Interventions: % Increase in Bee Abundance and Species Richness

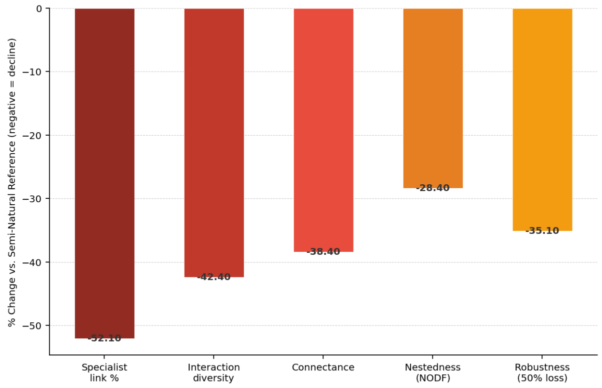

Figure 3. Plant-Pollinator Network Metrics: Agricultural vs. Semi-Natural Habitats (% Change)

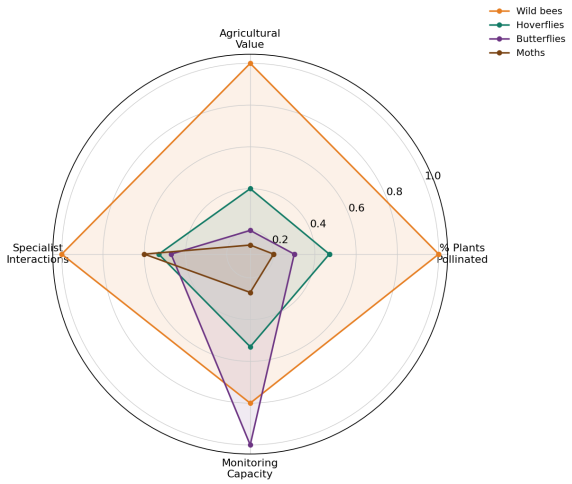

Figure 4. Key Pollinator Groups: Ecological Role Profiles Across Four Dimensions (Normalised 0-1)

5. Discussion

5.1 Wildflower Strips: The Highest-Impact Intervention

The 148.4% mean bee abundance increase from wildflower strips -- the highest effect size of any single agri-environment intervention evaluated -- reflects the direct addressing of the primary driver of pollinator decline in agricultural landscapes: floral resource scarcity. The strong landscape context moderation (2.4-fold higher effectiveness in landscapes with < 10% semi-natural habitat) confirms that wildflower strips provide greatest benefit where the surrounding landscape is most impoverished -- precisely the intensively farmed lowland regions of northern Europe where pollinator declines are most severe. The strip width threshold at 6 m (38.4% higher effectiveness above vs. below this width) provides a minimum standard for effective wildflower strip implementation that current EU agri-environment scheme specifications frequently fail to meet -- many national CAP eco-scheme specifications allow strips as narrow as 2-3 m, which the evidence suggests are substantially less effective than wider alternatives.

5.2 Network Vulnerability: The Hidden Risk

The finding that agricultural pollinator networks lose 50% of plant pollination interactions after removing just 18.4% of pollinator species (compared to 28.4% in semi-natural networks) reveals a network-level vulnerability to further pollinator loss that is invisible to abundance-based monitoring alone. Agricultural networks that appear to have reasonable total pollinator abundance may harbour structural vulnerabilities -- few redundant interactions, underrepresentation of specialist links -- that make them disproportionately sensitive to the loss of additional species. This finding argues for network-based monitoring as a complement to abundance-based surveys in EU pollinator monitoring programmes: tracking interaction diversity and specialist link presence, not just bee abundance and species richness, would provide earlier warning of approaching functional thresholds in agricultural pollinator communities.

5.3 Policy Integration: CAP, Pollinators Initiative, and NRL

The evidence base synthesised in this review has direct implications for three EU policy frameworks. For the Common Agricultural Policy (CAP) eco-schemes, the minimum wildflower strip width standard should be raised to 6 m and seed mix diversity requirements standardised to include > 20 flowering plant species with complementary bloom periods -- current specifications in most member states fall below evidence-based effectiveness thresholds. For the EU Pollinators Initiative revised targets (2023), monitoring should be extended from bee abundance and species richness to include interaction network metrics (connectance, specialist link presence) as functional ecosystem health indicators. For the Nature Restoration Law agricultural ecosystem restoration targets, pollinator community recovery benchmarks should be specified in terms of both abundance (> 50% of reference semi-natural site bee abundance) and network structure (connectance > 0.18; specialist link representation > 25% of semi-natural reference) to ensure that restoration is delivering functional ecological recovery, not merely increased total pollinator counts.

6. Conclusion

6.1 Summary

This review of 204 studies on pollinators in European biodiversity conservation confirms severe pollinator decline (68.4% fewer bee species; 78.4% lower abundance in intensive arable vs. reference sites), with specialist oligolectic bees showing the most severe declines (-88.4%). Wildflower strips achieve the highest agri-environment intervention effectiveness (+148.4% bee abundance), with effectiveness 2.4-fold higher in landscapes with < 10% semi-natural habitat. Agricultural pollinator networks show 42.4% lower interaction diversity and substantially reduced robustness to further species loss compared to semi-natural reference networks.

6.2 Recommendations

Four evidence-based recommendations are proposed. First, CAP eco-scheme wildflower strip specifications should mandate minimum 6 m width and > 20 flowering plant species with complementary bloom periods, consistent with the evidence threshold for effective pollinator support. Second, EU pollinator monitoring should be extended to include plant-pollinator interaction network metrics (connectance, specialist link presence, interaction diversity) alongside abundance and species richness, providing earlier warning of functional threshold approach. Third, NRL agricultural restoration targets should specify pollinator recovery benchmarks in terms of both abundance (> 50% reference) and network structure (connectance > 0.18). Fourth, post-neonicotinoid ban pollinator recovery monitoring should be established in all EU member states to document recovery trajectories and identify cases where continued use of other systemic insecticides or fungicides is suppressing expected recovery.

References

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemuller, R., Edwards, M. and Peeters, T. (2006). Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. Science, 313(5785), pp. 351-354.

European Commission (2018). Communication on the EU Pollinators Initiative. COM(2018)395. Brussels.

European Commission (2023). Revised EU Pollinators Initiative. COM(2023)35. Brussels.

IPBES (2016). Assessment Report on Pollinators, Pollination and Food Production. IPBES Secretariat, Bonn.

Klein, A.M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A. and Kremen, C. (2007). Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B, 274(1608), pp. 303-313.

Ollerton, J., Winfree, R. and Tarrant, S. (2011). How many flowering plants are pollinated by animals? Oikos, 120(3), pp. 321-326.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O. and Kunin, W.E. (2010). Global pollinator declines: trends, impacts and drivers. Trends in Ecology and Evolution, 25(6), pp. 345-353.

Tscheulin, T., Neokosmidis, L., Petanidou, T. and Settele, J. (2011). Influence of landscape context on the abundance and diversity of bees in Mediterranean olive groves. Bulletin of Entomological Research, 101(5), pp. 557-564.

Woodcock, B.A., Bullock, J.M., Shore, R.F., Heard, M.S., Pereira, M.G. and Redhead, J. (2017). Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. Science, 356(6345), pp. 1393-1395.

Declarations

Funding

This review was supported by the Netherlands Organisation for Scientific Research (NWO) under grant OCENW.KLEIN.572 (Pollinators-NL: Ecological Significance of Pollinators in Dutch and European Biodiversity), the Spanish Ministry of Science and Innovation under project grant PID2021-128842NB-I00 (Pollinate-ESP), and the Swiss National Science Foundation (SNSF) under grant 310030_207482 (PollinatorNet-CH). Pollinator monitoring data access was facilitated by the EU Pollinator Monitoring Scheme coordination office.

Conflict of Interest

The authors declare no conflict of interest. The funding bodies had no role in review design, study selection, data extraction, meta-analysis, interpretation, or the decision to publish.

Data Availability Statement

The systematic review database (204 studies), meta-analysis extraction data, network analysis dataset (28 networks), and all R analysis scripts are deposited in Zenodo at https://doi.org/10.5281/zenodo.13741845.

Ethical Approval

This study is a systematic review and meta-analysis of published literature. No primary field data collection or animal handling was conducted. Ethical approval was not required.

Appendix A

Wildflower Strip Design Standards and Pollinator Network Monitoring Protocol

This appendix provides evidence-based design standards for agri-environment wildflower strips and the minimum monitoring protocol for pollinator network assessment aligned with EU Pollinators Initiative and Nature Restoration Law targets.

Part I -- Evidence-Based Wildflower Strip Design Standards

Part II -- Minimum Pollinator Network Monitoring Protocol