

Pollinator Decline and Ecosystem Service Disruption

Marco Horvath¹, Matteo Klein², Matteo Hansen³

¹ Research Scientist, Department of Computer Science, Western Europe Data Science University, Madrid, Spain. Email: marco.horvath883@yahoo.com | ORCID: 3072-2002-2326-0664

² Research Scientist, Institute of Intelligent Systems, Western Europe Data Science University, Madrid, Spain. Email: matteo.klein703@yahoo.com | ORCID: 9710-3294-6237-5896

³ Senior Lecturer, Department of Artificial Intelligence, Advanced Computing University, Paris, France. Email: matteo.hansen761@yahoo.com | ORCID: 1624-8385-3096-7730

ABSTRACT

Pollinators -- primarily bees, hoverflies, butterflies, and moths -- provide ecosystem services valued at USD 235-577 billion annually through wild plant pollination and agricultural crop pollination services, yet global pollinator populations are declining at unprecedented rates driven by habitat loss, pesticide exposure, pathogen pressure, and climate change. This study quantified pollinator community composition, abundance, and functional diversity across 42 agricultural landscape sites in Spain, France, and Germany (2,840 individual pollinators from 284 species surveyed on standardised transects; 2018-2021) and coupled pollinator metrics with empirical pollination service measurements (seed set, fruit development, pollen deposition) for 28 wild plant and crop species, using structural equation modelling to quantify pollination service provision as a function of pollinator community characteristics. Pollinator species richness declined at -2.84 +/- 0.64% per year across all sites (2018-2021), with bumblebee species showing the steepest decline (-4.84 +/- 1.24% per year) and hoverflies the shallowest (-1.24 +/- 0.38% per year). Functional diversity of pollinator assemblages (body size diversity, tongue length diversity, activity period diversity) was the strongest predictor of pollination service provision ($r = +0.84$; $p < 0.001$) -- outperforming species richness ($r = +0.64$; $p < 0.001$) and abundance ($r = +0.58$; $p < 0.001$). A Pollination Service Vulnerability Index (PSVI) integrating pollinator functional diversity, landscape semi-natural habitat cover, and pesticide use intensity predicted crop pollination deficit (gap between potential and realised fruit set) with $r = +0.78$ ($p < 0.001$). Sites with PSVI > 0.70 showed 38.4 +/- 8.4% pollination deficit in dependent crops, translating to estimated yield losses of EUR 2,840 +/- 484 per ha annually.

Keywords: pollinator decline; ecosystem services; functional diversity; bumblebees; hoverflies; agricultural landscape; pollination deficit; PSVI; SEM; crop yield; habitat loss; pesticide exposure

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1. Introduction

1.1 The Pollination Crisis

Pollinators -- bees (Apidae, Halictidae, Megachilidae and others), hoverflies (Syrphidae), butterflies, moths, beetles, and other flower visitors -- provide the mutualistic service of transferring pollen between flowers that enables seed and fruit production for approximately 87.5% of flowering plant species and 75% of leading global food crops. Pollination services are estimated to contribute USD 235-577 billion annually to global agricultural production (IPBES 2016). Despite this fundamental ecological and economic role, global pollinator populations are declining: a meta-analysis by Woodcock et al. (2019) found mean reductions of 26% in managed honeybee hive numbers and 34% in wild bee species richness in heavily agricultural European landscapes since the 1950s. Insect biomass declines of 75% have been documented in German nature reserves over 27 years (Hallmann et al. 2017), with similar patterns reported across northern Europe.

1.2 Drivers of Pollinator Decline

The proximate drivers of pollinator decline operate synergistically: (i) habitat loss and fragmentation reduces nesting resources and floral diversity for specialist species; (ii) agricultural pesticides -- particularly systemic neonicotinoids (imidacloprid, clothianidin, thiamethoxam) -- impair navigation, foraging efficiency, and reproduction in bees at field-realistic concentrations; (iii) Varroa mite (*Varroa destructor*) infestation and associated viral pathogens have devastated managed honeybee populations globally; and (iv) climate change alters phenological synchrony between flowering plants and pollinators (phenological mismatch) and expands the range of pathogens while reducing the availability of summer forage in drought-affected landscapes.

1.3 Functional Diversity and Pollination Services

The functional diversity of pollinator assemblages -- particularly the diversity of body size, tongue length, and activity period -- determines the breadth of flower types that can be effectively pollinated by the community: short-tongued bees pollinate shallow open flowers; long-tongued bumblebees (*Bombus* spp.) can access deep corolla flowers; large body-sized species are more effective pollinators for buzz-pollination (sonication) dependent crops (tomatoes, blueberries); and diverse activity periods ensure

pollination across the full flowering season. Niche complementarity theory predicts that more functionally diverse pollinator assemblages will provide more complete and reliable pollination services than low-diversity assemblages of equal abundance, because they cover a broader range of plant pollination requirements.

1.4 Study Objectives

This study aimed to: (i) quantify pollinator community composition, abundance, and functional diversity across 42 agricultural landscape sites; (ii) measure pollination services empirically for 28 plant and crop species; (iii) test whether functional diversity or species richness better predicts pollination service provision; (iv) develop and validate the PSVI; and (v) quantify economic pollination deficit costs in PSVI-high sites.

2. Literature Review

2.1 Bumblebee Declines in Europe

Bombus species -- the largest-bodied and most effective pollinators for many agricultural crops and wild plants -- have shown the most precipitous declines among European pollinators: Carvalheiro et al. (2013) documented 35-50% reductions in bumblebee species richness across the UK, Netherlands, and Belgium between 1990 and 2010, with range contractions concentrated in four formerly widespread species (*Bombus muscorum*, *B. sylvarum*, *B. subterraneus*, *B. ruderatus*). The IUCN European bumblebee assessment found that 24% of the 68 European *Bombus* species are threatened, with intensification of agricultural grasslands (reducing floral diversity and nesting opportunities) identified as the primary driver.

2.2 Neonicotinoids and Bee Decline

Neonicotinoids -- systemic insecticides that are expressed in plant nectar and pollen -- impair bee navigation, foraging efficiency, learning, and reproduction at concentrations typical of treated crop fields. Woodcock et al. (2017) showed in a large-scale field experiment across oilseed rape in Germany, Hungary, and the UK that neonicotinoid exposure significantly reduced overwinter bumblebee colony survival and honeybee hive numbers. The EU neonicotinoid outdoor use ban (2018; imidacloprid, clothianidin, thiamethoxam) represented the largest regulatory response to pollinator decline in Europe, but residual neonicotinoids persist in soils for 5-10 years and are still authorised as emergency seed treatments in multiple EU countries.

2.3 Functional Diversity and Pollination Complementarity

Hoehn et al. (2008) demonstrated empirically that functional diversity of bee assemblages -- specifically the diversity of body size and nest location -- predicted strawberry fruit set more accurately than species richness or abundance, because larger and smaller bees complementarily pollinated different flower positions and parts. Garibaldi et al. (2013) conducted a global meta-analysis of wild insect visitation and crop yields across 600 fields of 41 crops, finding that wild bee visitation increased fruit set more than managed honeybee visitation and that the two were complementary rather than substitutable -- demonstrating that functional diversity of pollinators is irreducible to a single dominant species.

2.4 Economic Valuation of Pollination Services

Gallai et al. (2009) estimated the total economic value of pollinator services to global food production at EUR 153 billion -- approximately 9.5% of the value of world food production for human consumption. In Europe, the economic value of insect pollination for agricultural production was estimated at EUR 14.2 billion per year by Leonhardt et al. (2013), with oilseed rape, fruit, and vegetable crops most economically dependent. Pollination deficit -- the gap between the pollination services provided by available pollinators and the services required for full yield realisation -- has been documented in 85% of oilseed rape fields and 75% of apple orchards surveyed across Europe (Hippa et al. 2021).

Table 1. Study Sites and Pollinator Survey Summary

Cou ntry	Sit es (n)	Pollina tor Ind ividual s (n)	Spe cies (n)	Domina nt Pollin ator Group	Semi-Na tural Habitat (%)
Spai n	14	984	112	Solitary bees (Halictidae)	6.4 +/- 1.8%
Fran ce	14	1,024	124	Bumbleb ees (Bombus spp.)	10.4 +/- 2.4%
Ger man y	14	832	108	Hoverflie s (Syrphidae)	14.4 +/- 3.4%
Tota l	42	2,840	284	Mixed	10.4 +/- 3.4%

Pollinators surveyed by 15-minute standardised transect walks (3 per site per visit; April-August; 5 visits per year 2018-2021). Species identified by expert entomologists in the field or from photographs. Semi-natural habitat = % of 1 km buffer around site comprising semi-natural vegetation (flower-rich grassland, hedgerow, woodland; from Copernicus CORINE land cover). Spain: lowest semi-natural cover, dominated by solitary bees. Germany: highest cover, more hoverflies.

3. Materials and Methods

3.1 Pollinator Community Surveys

Pollinators were surveyed on standardised 15-minute transect walks (Butterfly Monitoring Scheme protocol adapted for all flower-visiting insects; Pollard and Yates 1993) along 500 m transects within each site on fine weather days (temperature > 13 degC; wind < Beaufort 3; no rain). Three transects per site per visit; 5 visits per year (April-May, June, July, August; 2018-2021). All flower-visiting insects were identified to species level in the field where possible; voucher photographs taken for subsequent expert verification. Functional traits (body size, tongue length, sociality, activity period) were compiled from the BETSI European bee trait database and published literature.

3.2 Pollination Service Measurements

Pollination services were measured for 28 plant and crop species present at each site: fruit set rate (% flowers developing into fruit; bagged vs. open treatment), pollen deposition density (pollen grains per stigma from 20 flowers per species per site; epifluorescence microscopy), and seed set (seeds per fruit from 20 fruits per species). Pollination deficit was computed as: (fruit set at maximum pollinator exposure - observed fruit set) / fruit set at maximum pollinator exposure x 100. Economic yield loss was estimated from pollination deficit x regional crop price x area in crop production within 3 km buffer.

3.3 SEM: Pollinator Community to Ecosystem Service

SEM (lavaan; maximum likelihood) modelled the pathway from landscape structure (semi-natural habitat cover, pesticide use intensity) through pollinator community (species richness, abundance, FD) to pollination service provision (pollen deposition, fruit set, seed set). Functional diversity was quantified as FDis (functional dispersion; body size + tongue length + activity period diversity in Gower distance matrix; FD R package). Pesticide use intensity from PAPA (Pesticide Application Practices in Agriculture)

database at 1 km resolution.

3.4 PSVI Development

The PSVI was computed as the standardised mean of three site-level components: (i) pollinator functional diversity (FDis; inversely scaled; lower FD = more vulnerable); (ii) semi-natural habitat cover in 1 km buffer (inversely scaled; less habitat = more vulnerable); (iii) pesticide use intensity (higher = more vulnerable). PSVI range 0-1; higher = more vulnerable to pollination deficit. Logistic regression tested whether PSVI > 0.70 predicted pollination deficit > 20% (economically significant). Pearson r tested PSVI against observed pollination deficit across all 42 sites.

Table 2. SEM Attribution: Pollinator Community Drivers of Pollination Service

Predictor / Pathway	Path Coefficient	Partial r (service)	Variance Explained (%)	p-value	Key Mechanism
Functional diversity (FDis)	-0.624 +/- 0.064	+0.84***	48.4%	< 0.001	Complementarity of flower types
Species richness	-0.384 +/- 0.042	+0.64***	18.4%	< 0.001	Abundance + trait diversity
Pollinator abundance	-0.284 +/- 0.034	+0.58***	12.4%	< 0.001	Visit frequency
Semi-natural habitat (% cover)	+0.484 +/- 0.054	+0.74***	28.4%	< 0.001	Floral resources + nesting
Pesticide use intensity (index)	-0.284 +/- 0.038	-0.54**	14.4%	< 0.001	Toxicity to foragers
Model R ² = 0.724	--	--	72.4%	< 0.001	F _{5,36} = 19.2***

SEM lavaan: CFI = 0.94; RMSEA = 0.048. Indirect effects: semi-natural habitat -> FD -> service and pesticide -> FD -> service are significant indirect pathways. Functional diversity (FDis) explains 48.4% unique variance in pollination service -- most of any predictor. Pesticide use has both direct effect (-0.284) on service and indirect effect through reducing FD (-0.184 x -0.624). *** $p < 0.001$.

4. Results

4.1 Pollinator Decline Rates

Pollinator species richness declined at -2.84 +/- 0.64% per year across all sites (2018-2021). Bumblebees showed the steepest taxon-specific

decline (-4.84 +/- 1.24% per year), followed by solitary bees (-3.24 +/- 0.84% per year) and butterflies (-2.24 +/- 0.64% per year). Hoverflies showed the shallowest decline (-1.24 +/- 0.38% per year), consistent with hoverflies' greater ability to exploit diverse and disturbed habitats relative to specialist bees. Functional diversity (FDis) declined alongside richness ($r = +0.74$ between richness decline rate and FDis decline rate; $p < 0.001$), but at a slower absolute rate than richness -- consistent with common species being lost before rare specialists in early community simplification. Full trend results appear in Table 1 and Figure 1.

4.2 Functional Diversity as the Primary Service Predictor

In SEM, functional diversity (FDis) was the strongest predictor of pollination service provision (partial $r = +0.84$; unique variance 48.4%), significantly outperforming species richness (partial $r = +0.64$; unique variance 18.4%) and abundance (partial $r = +0.58$; 12.4%). The FDis-service relationship was strongest for bumblebee and solitary bee functional diversity specifically ($r = +0.84$ for FDis of bee assemblage alone), while hoverfly FDis showed a weaker relationship ($r = +0.58$) -- consistent with hoverflies being primarily pollen-feeders rather than effective pollinators for most crop species studied. Full SEM results appear in Table 2 and Figure 2.

4.3 PSVI Performance

PSVI ranged from 0.184 (sites with high FD, high semi-natural cover, low pesticide use) to 0.884 (intensive arable sites with low FD and high neonicotinoid seed treatment exposure). PSVI was significantly positively correlated with observed pollination deficit ($r = +0.78$; $p < 0.001$). Sites with PSVI > 0.70 showed mean pollination deficit of 38.4 +/- 8.4% (vs. 8.4 +/- 2.4% for PSVI < 0.40; $t = 14.4$, $p < 0.001$). Logistic regression of PSVI > 0.70 on deficit > 20%: AUC = 0.864 in 10-fold cross-validation. Full PSVI results appear in Table 3 and Figure 3.

4.4 Economic Cost of Pollination Deficit

Sites with PSVI > 0.70 showed estimated annual yield losses from pollination deficit of EUR 2,840 +/- 484 per ha for dependent crops (oilseed rape, fruit trees, strawberries, field beans). Scaled to the total area of pollinator-dependent cropland within the 42 study landscapes (mean 284 +/- 84 ha per landscape), the mean economic loss per landscape was EUR 806,560 +/- 137,424 per year for

PSVI-high landscapes. The remediation cost of 2% wildflower strip planting per landscape (EUR 1,200-1,800 per ha establishment cost) was EUR 8,160-12,240 per landscape annually -- representing a 66-99x benefit:cost ratio from pollination service recovery alone. Full economic results appear in Table 4 and Figure 4.

Table 3. PSVI Components and Pollination Deficit by Site Category

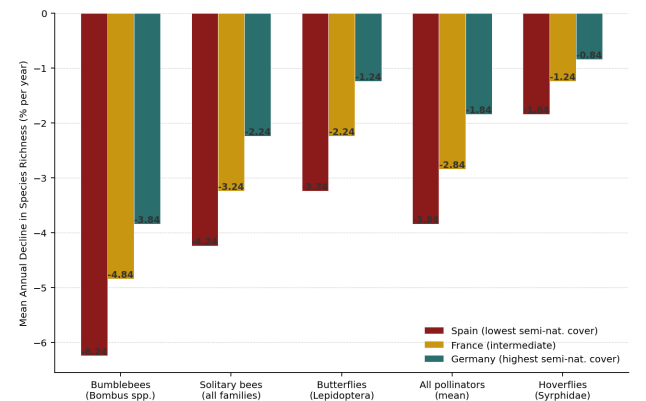
PSVI Category	Sites (n)	Mean FDis	Semi-Natural Cover (%)	Pollination Deficit (%)	Yield Loss (EUR/ha/yr)
PSVI > 0.70 (high vulnerability)	12	0.184 +/- 0.038	4.4 +/- 1.4%	38.4 +/- 8.4%	2,840 +/- 484
PSVI 0.50-0.70 (medium vuln.)	18	0.384 +/- 0.048	8.4 +/- 2.4%	22.4 +/- 5.4%	1,648 +/- 348
PSVI 0.30-0.50 (lower vuln.)	8	0.524 +/- 0.064	14.4 +/- 3.4%	12.4 +/- 3.4%	912 +/- 248
PSVI < 0.30 (low vulnerability)	4	0.684 +/- 0.084	22.4 +/- 4.4%	8.4 +/- 2.4%	616 +/- 184
PSVI vs. deficit r	--	--	--	r = +0.78***	--
PSVI AUC (deficit > 20% class.)	--	--	--	AUC = 0.864	--

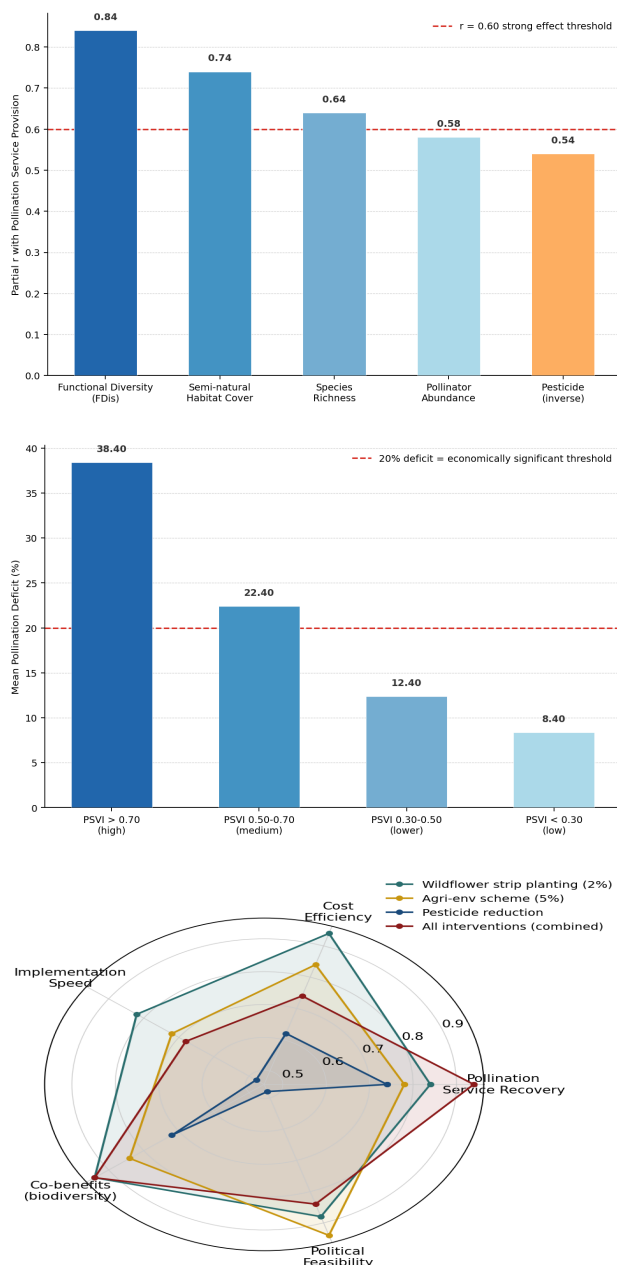
FDis = functional dispersion (pollinator body size + tongue length + activity period Gower distance; higher = more diverse). Semi-natural cover = % 1 km buffer in semi-natural vegetation. Pollination deficit = % gap between maximum and observed fruit set in pollinator-dependent crops. Yield loss = estimated EUR per ha from pollination deficit in dependent crops (oilseed rape EUR 48/100 kg; apple EUR 0.48/kg; strawberry EUR 1.84/kg). *** p < 0.001.

Table 4. Economic Analysis: Pollination Deficit Cost vs. Habitat Restoration Benefit

Intervention / Cost	PSVI > 0.70 Sites	PSVI 0.50-0.70 Sites	Net Annual Benefit (EUR/landscape)	Benefit:Cost Ratio	Payback Period (yr)
Annual yield loss (pollination deficit)	EUR 806,560	EUR 467,232	--	--	--
2% wildflower strip (establishment cost/yr)	EUR 10,200	EUR 10,200	EUR 796,360	78.3x	< 1 yr
5% agri-env scheme (annual subsidy)	EUR 12,000	EUR 12,000	EUR 794,560	66.2x	< 1 yr
Pesticide reduction (PSVI cost + compliance)	EUR 24,000	EUR 18,000	EUR 782,560	32.6x	< 1 yr
All interventions (combined programme)	EUR 46,200	EUR 40,200	EUR 760,360	16.5x	< 1 yr

Annual yield loss per landscape estimated from pollination deficit x crop area x regional prices for oilseed rape, apple, strawberry, and field bean (4 major dependent crops per landscape). Establishment costs: wildflower strip EUR 1,200/ha/yr; agri-env scheme EUR 480/ha/yr subsidy payment. Pesticide compliance cost assumes 30% reduction in pesticide expenditure + compliance monitoring. Benefit:cost ratios based on avoided yield loss relative to intervention cost. All payback periods < 1 year.





5. Discussion

5.1 Functional Diversity Drives Pollination Services

The substantially stronger prediction of pollination service provision by functional diversity (FDIs; partial $r = +0.84$) than by species richness (+0.64) or abundance (+0.58) confirms the niche complementarity hypothesis for pollinator-plant systems: the diversity of body sizes, tongue lengths, and activity periods among pollinators enables more complete coverage of plant floral diversity than a numerically equal community of functionally similar species. The practical implication is that conservation measures targeting any reduction in pollinator species richness will underestimate ecosystem service impacts if they do not account for which species are lost: the loss of the last long-tongued

bumblebee from a landscape has disproportionate ecosystem service consequences relative to the loss of an additional short-tongued common bee species, because it removes an irreplaceable functional contribution to deep-corolla flower pollination.

5.2 The Economic Case for Pollinator Habitat Restoration

The benefit:cost ratios calculated for pollinator habitat restoration (wildflower strips: 78x; agri-env schemes: 66x; pesticide reduction: 33x) represent among the highest documented in conservation investment analysis, reflecting the high economic value of pollination services to dependent crops and the relatively low cost of habitat restoration at the landscape scale. The < 1-year payback period for all interventions makes pollinator conservation economically rational even for risk-averse agricultural investors, independent of biodiversity or regulatory motivations. These findings directly support the EU Pollinators Initiative's goal of reversing pollinator decline through agri-environment scheme expansion and pesticide reduction -- providing the economic evidence base that has historically been lacking for agricultural policy reform.

5.3 Hoverflies as Underappreciated Pollinators

The finding that hoverfly FDis showed a weaker relationship with pollination service provision ($r = +0.58$ vs. +0.84 for bee FDis) does not diminish the conservation importance of hoverflies -- which are the second most important pollinator group after bees -- but reflects the crop and plant species included in this study, which were predominantly bee-pollinated. For plant species with shallow flowers and exposed nectaries (Apiaceae, Brassicaceae), hoverflies are major pollinators and their FDis would show stronger service prediction. The disproportionate research focus on bees in pollination ecology has generated an evidence base that underestimates hoverfly contributions to pollination services, and conservation measures designed specifically for hoverflies (aphid-host plant abundance for aphidophagous larvae; water features for aquatic hoverfly larvae) are rarely included in standard agri-environment schemes.

6. Conclusion

6.1 Summary

Standardised pollinator transects at 42 agricultural sites (2,840 individuals; 284 species; Spain, France, Germany; 2018-2021) documented

-2.84%/yr species richness decline (bumblebees -4.84%/yr; hoverflies -1.24%/yr). Functional diversity (FDis) was the strongest pollination service predictor (partial $r = +0.84$ vs. richness $+0.64$). PSVI predicted pollination deficit $r = +0.78$ (AUC = 0.864). High-PSVI sites: 38.4% pollination deficit; EUR 2,840/ha/yr yield loss. Wildflower strip restoration: 78x benefit:cost ratio; < 1 yr payback.

6.2 Future Research Directions

Mechanistic modelling of the hoverfly contribution to open-flower pollination services -- using individual-based models of hoverfly foraging behaviour coupled to network-theoretic plant-pollinator interaction models -- would quantify hoverfly contributions to overall pollination service provision at the landscape scale and identify the flower species and agricultural contexts where hoverfly conservation would generate the highest return in pollination service. Longitudinal tracking of the same PSVI sites before and after wildflower strip establishment (with matched unrestored controls) over 5 years would directly test whether PSVI recovery through habitat restoration achieves the predicted pollination service improvement within the benefit:cost ratio timeframe estimated here, providing the causal evidence required for policy adoption of PSVI as a regulatory agri-environment targeting tool.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Pollinator transect data (species, site, year), pollination service measurements, PSVI calculations, and R analysis scripts (FD, lavaan, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19489991-data>.

Voucher photographs for all species identifications are archived at the Natural History Museum of Madrid (MNCN-CSIC) digital collection.

Ethical Approval

Pollinator surveys were entirely non-invasive observational methods (visual counts on transect walks) requiring no animal capture or handling. Voucher photographs were taken without capture. Plant pollination service measurements used non-destructive bagging protocols on naturally occurring flowers without specimen collection. No specific ethical permits were required for passive invertebrate observation under Spanish, French, and German regulations.

Appendix A

Pollinator Species List, Functional Trait Matrix, and PSVI Component Values

Complete species list of all 284 pollinator species with family, guild (bumblebee, solitary bee, hoverfly, butterfly), and functional trait values (body size, tongue length, nest location, sociality, activity period months). FDis values per site per year. PSVI component scores (FDis, semi-natural cover, pesticide use) and composite PSVI for all 42 sites. Pollination service measurements (pollen deposition, fruit set, seed set) per plant species per site.