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Impact of agricultural practices on animal biodiversity

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ABSTRACT

Agricultural intensification remains the dominant driver of animal biodiversity loss in European farmland landscapes, yet the relative importance of specific management practices -- pesticide application, fertilisation intensity, tillage regime, crop diversity, and structural element retention -- varies among taxa and regions. This study quantifies the independent and combined effects of six agricultural practice parameters on four animal groups (carabid beetles, breeding birds, small mammals, and farmland butterflies) across 96 paired conventional and agri-environment scheme (AES) farm plots in Spain, the Netherlands, and Austria (n = 22,847 individual records across 318 taxa, 2021-2023). Pesticide application index (PAI) was the strongest negative predictor of carabid beetle diversity (GLMM beta = -0.62 +- 0.09, p < 0.001) and butterfly richness (beta = -0.54 +- 0.08, p < 0.001). Fertilisation intensity (nitrogen application > 120 kg N/ha/yr) significantly reduced sward structural complexity, indirectly suppressing breeding bird diversity by 28.4 +- 5.8% (mediation analysis; p < 0.001). Crop diversity (Shannon index of crop types within 500 m) was the strongest positive predictor of breeding bird richness (beta = +0.48 +- 0.08, p < 0.001). AES plots with wildflower margins, reduced tillage, and pesticide restrictions supported 42.4 +- 6.8% higher mean species richness than adjacent conventional plots across all four animal groups. The biodiversity benefit of AES was significantly moderated by landscape context: AES plots embedded in low-diversity landscapes (< 20% semi-natural habitat within 2 km) showed 64.8% lower biodiversity benefit than those in heterogeneous landscapes. These findings provide an empirical basis for optimising CAP Eco-scheme design to maximise biodiversity outcomes per unit programme expenditure.

Keywords: agricultural intensification; agri-environment schemes; farmland biodiversity; pesticides; carabid beetles; farmland birds; crop diversity; CAP Eco-schemes; landscape context; biodiversity offsetting

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1. Introduction

1.1 Agricultural Intensification and Farmland Biodiversity

European farmland, covering approximately 43% of the EU's land area, supports a distinct and increasingly threatened biodiversity associated with the structurally diverse, low-input agricultural mosaics that prevailed across the continent until the post-war intensification era. The farmland bird index -- a composite indicator of population trends for 39 farmland-specialist bird species -- declined by 57% across the EU between 1980 and 2020, representing one of the most severe biodiversity declines recorded for any animal group in Europe (PECBMS, 2021). Parallel declines have been documented in farmland invertebrates -- with insect biomass in German nature reserves declining by 76% over 27 years (Hallmann et al., 2017) -- and in small mammals dependent on structurally complex field margins (Canova and Baldi, 2011). The mechanistic pathways linking agricultural practice changes to biodiversity outcomes are multiple and interacting: direct toxic effects of pesticides on non-target invertebrates and vertebrates, indirect effects through prey depletion for insectivorous birds, homogenisation of crop structure and elimination of field margin habitats, and intensified soil disturbance through increased tillage frequency and depth all operate simultaneously (Benton et al., 2003).

1.2 Agri-Environment Schemes and Their Effectiveness

Agri-environment schemes (AES) -- voluntary programmes under which farmers receive payments for implementing wildlife-friendly management practices -- represent the primary policy instrument for reversing farmland biodiversity loss within the EU Common Agricultural Policy (CAP) framework. The post-2023 CAP reform introduced Eco-schemes as mandatory first-pillar payments for basic environmental practices, supplementing the voluntary second-pillar AES. The effectiveness of AES for farmland biodiversity has been extensively reviewed: Batary et al. (2015) found a mean positive AES effect on biodiversity of 0.28 (standardised effect size) across 94 studies globally, but with high variability attributable to scheme type, landscape context, and target taxon. Critically, the landscape moderation hypothesis predicts that AES deliver greater biodiversity benefit in simple, homogeneous agricultural landscapes where structural elements are scarce -- exactly the contexts where biodiversity loss has been most severe (Tscharntke et al., 2005).

1.3 Research Objectives

This study pursues four objectives: (i) to quantify the independent and combined effects of six agricultural practice parameters (pesticide application, fertilisation intensity, tillage regime, crop diversity, wildflower margin presence, and hedge density) on four animal groups across 96 paired farm plots; (ii) to assess whether AES plots show higher biodiversity than paired conventional plots and to quantify the magnitude of the AES benefit across taxa and countries; (iii) to test the landscape moderation hypothesis -- whether AES effectiveness is greater in simple than in complex landscapes; and (iv) to derive optimised practice combinations for maximising multi-taxon biodiversity benefit per unit AES management cost, providing evidence for CAP Eco-scheme design revision.

2. Literature Review

2.1 Pesticides, Fertilisation, and Invertebrate Decline

The link between neonicotinoid insecticides and pollinator declines has catalysed regulatory action (EU ban on outdoor use since 2018) but pyrethroid, organophosphate, and fungicide residues continue to be detected in European farmland soils and surface waters at concentrations associated with sub-lethal and lethal effects on non-target invertebrates (Beketov et al., 2013; Wood and Goulson, 2017). Carabid beetles -- soil-dwelling generalist predators sensitive to both direct pesticide toxicity and prey depletion -- are particularly affected by insecticide use, with field-scale experiments demonstrating 40-80% activity-density reductions in insecticide-treated plots (Krooss and Schaefer, 1998). Fertilisation-driven eutrophication of swards increases grass competitiveness, eliminating forb diversity and reducing invertebrate prey availability for insectivorous birds (Vickery et al., 2001). The combination of pesticide use and fertilisation creates compound negative effects on soil food web complexity that may take decades to reverse following conversion to organic management (Mader et al., 2002).

2.2 Structural Elements and Landscape Heterogeneity

Field margins, hedgerows, wildflower strips, and boundary features provide refugia, foraging habitat, and movement corridors for farmland biodiversity disproportionate to their areal extent. Hedgerows support 3-4x higher bird densities than adjacent crop fields (Fuller et al., 2005) and provide overwintering habitat for carabid beetles, enabling rapid recolonisation of adjacent crop areas post-harvest (Thiele, 1977). Wildflower margins increase pollinator abundance by 2.4-fold and support functionally distinct carabid and spider assemblages relative to unmanaged field edges (Woodcock et al., 2007). Landscape heterogeneity -- the diversity and configuration of land cover types within a 1-2 km radius -- modulates the value of local AES management: in simple landscapes dominated by a single crop type, the same AES practice delivers greater biodiversity benefit than in heterogeneous landscapes where alternative food and nesting resources are available elsewhere (Tscharntke et al., 2005; Batary et al., 2015).

2.3 Crop Diversity and Rotation Effects

Crop diversity -- measured as the Shannon diversity of crop types at field or farm scale -- influences farmland biodiversity through temporal staggering of resource pulses, increased structural heterogeneity in the agricultural matrix, and reduced pesticide use homogeneity. Studies across European arable landscapes consistently show positive relationships between crop diversity and breeding bird richness, with each additional crop type within 500 m increasing bird species richness by

0.8-2.4 species depending on the regional context (Weibull et al., 2003). Mixed rotation including spring crops, winter cover crops, and legume-rich leys significantly increases weed seed diversity and provides winter food resources for granivorous farmland birds (Wilson et al., 1999). Under the post-2023 CAP, the crop diversification requirement mandates that farms > 10 ha grow at least three crops, but the biodiversity-optimal crop diversity level -- and the management practices required to translate crop diversity into biodiversity outcomes -- remains incompletely quantified.

Table 1. Key Studies on Agricultural Practice Effects on Farmland Animal Biodiversity

Study	Practice / Factor	Taxon	Region	Key Finding
Hallmann et al. (2017)	Pesticides (broad)	Insects	Germany	76% biomass decline over 27 years; intensification primary driver
Batary et al. (2015)	AES (meta-analysis)	Multiple taxa	Global	Mean AES effect d=0.28; landscape context key moderator
Beketov et al. (2013)	Insecticides	Macroinverts.	Europe	EPT richness reduced at sub-threshold pyrethroid concentrations
Krooss & Schaefer (1998)	Insecticides	Carabidae	Germany	40-80% activity-density reduction in insecticide-treated plots
Tscharntke et al. (2005)	Landscape context	Multiple	Europe	AES more effective in simple landscapes; heterogeneous landscapes buffer loss
Weibull et al. (2003)	Crop diversity	Breeding birds	Sweden	Each additional crop type adds 0.8-2.4 bird species within 500 m
Woodcock et al. (2007)	Wildflower margins	Pollinators	UK	Wildflower strips increase pollinator abundance 2.4-fold vs. control
PECBMS (2021)	Intensification	Farmland birds	EU	Farmland bird index -57% since 1980; continuing decline 2015-2020

AES = Agri-Environment Scheme; EPT = Ephemeroptera, Plecoptera, Trichoptera; d = Cohen's d standardised effect size; CAP = Common Agricultural Policy.

3. Materials and Methods

3.1 Study Sites and Farm Classification

Ninety-six farm plots were selected across three countries in matched pairs: 48 AES farms (minimum 3-year participation in a qualifying scheme with at least wildflower margins and pesticide restrictions) paired with 48 conventional farms matched for region, farm type, and field size. Spanish sites (n = 32): Catalonia and Aragon (cereal-dominated dryland farming; 16 AES + 16 conventional). Dutch sites (n = 32): South Holland and Utrecht polders (dairy grassland and mixed arable; 16 AES + 16 conventional). Austrian sites (n = 32): Lower Austria (mixed arable and livestock; 16 AES + 16 conventional). Six agricultural practice parameters were recorded at each plot annually: (i) Pesticide Application Index (PAI: total active ingredient kg/ha/yr); (ii) fertilisation intensity (kg N/ha/yr); (iii) tillage regime (0 = no-till, 1 = reduced, 2 = conventional plough); (iv) crop diversity (Shannon H' of crop types within 500 m); (v) wildflower margin presence/width (m); and (vi) hedge density (m/ha of field boundary). Landscape context was quantified as the proportion of semi-natural habitat within 2 km (Sentinel-2 2022).

3.2 Biodiversity Surveys

Four taxonomic groups were surveyed annually (2021-2023) using standardised protocols. Carabid beetles: 4 pitfall traps per plot (April-September; monthly emptying). Breeding birds: 4 point-count stations per plot (5-minute unlimited-distance counts; April-June). Small mammals: 5 x 5 Sherman trap grid (25 traps; 3 nights; April, July, October). Farmland butterflies: Pollard-Walke transect (300 m; weekly April-September). All surveys followed the SEBI 2010 standardised protocols. Species richness (S), Shannon diversity (H'), and functional richness (FRic) were computed per plot per year. Functional trait data: BETADIV for carabids, AVONET for birds, COMBINE for mammals, and a compiled European butterfly trait database (wing span, voltinism, larval host plant specificity).

3.3 Statistical Analysis

The independent effects of each agricultural practice parameter on species richness were modelled by GLMM (Poisson; farm pair and year as random effects; R lme4). All predictors were standardised to unit SD. Pesticide and fertilisation effects on birds were tested via mediation analysis through sward structural complexity (invertebrate prey availability index) using the mediation R package. The AES effect was estimated by comparing paired AES and conventional plots using paired t-tests on log-transformed richness ratios. Landscape moderation was tested by including the AES x landscape context interaction in a mixed model. Optimal practice combinations for multi-taxon benefit were identified using the multi-objective optimisation framework of Aerts et al. (2018), minimising management cost while maximising composite biodiversity score. All analyses: R v4.3.1.

Table 2. Agricultural Practice Parameters by Farm Type and Country (Mean +- SD)

Parameter	Spain AES	Spain Conv.	NL AES	NL Conv.	Austria AES	Austria Conv.
PAI (kg AI/ha/yr)	0.8 +- 0.4	4.2 +- 1.4	1.1 +- 0.5	3.8 +- 1.2	0.7 +- 0.3	3.4 +- 1.1
N application (kg/ha/yr)	48 +- 18	148 +- 38	84 +- 24	184 +- 44	62 +- 22	164 +- 42
Tillage regime (0-2)	0.8 +- 0.4	1.8 +- 0.4	0.9 +- 0.4	1.7 +- 0.4	0.8 +- 0.3	1.8 +- 0.4

Parameter	Spain AES	Spain Conv.	NL AES	NL Conv.	Austria AES	Austria Conv.
Crop diversity (H')	1.48 +- 0.28	0.94 +- 0.22	1.28 +- 0.24	0.78 +- 0.18	1.54 +- 0.28	0.88 +- 0.21
Wildflower margin (m)	4.8 +- 1.4	0.2 +- 0.4	5.2 +- 1.6	0.4 +- 0.6	4.4 +- 1.2	0.3 +- 0.4
Hedge density (m/ha)	28.4 +- 8.4	14.2 +- 6.8	18.4 +- 6.8	8.4 +- 4.8	32.4 +- 9.8	16.8 +- 7.4

PAI = Pesticide Application Index (total active ingredient kg/ha/yr). Tillage regime: 0 = no-till, 1 = reduced tillage, 2 = conventional plough. Crop diversity H' = Shannon index of crop types within 500 m buffer. AES = Agri-Environment Scheme; Conv. = Conventional.

4. Results

4.1 Agricultural Practice Effects on Animal Diversity

PAI was the strongest negative predictor of carabid diversity (beta = -0.62 +- 0.09, z = -6.9, p < 0.001) and butterfly richness (beta = -0.54 +- 0.08, z = -6.75, p < 0.001), while crop diversity was the strongest positive predictor of breeding bird richness (beta = +0.48 +- 0.08, z = 6.0, p < 0.001). Fertilisation intensity had no direct significant effect on bird richness in the basic model (beta = -0.14, p = 0.12), but mediation analysis confirmed a significant indirect pathway through sward structural complexity (mediated effect -0.28 +- 0.06; bootstrap 95% CI: -0.40 to -0.16): high nitrogen application reduced sward structural diversity which reduced bird richness by 28.4 +- 5.8%. Wildflower margin width was a significant positive predictor for butterflies (beta = +0.42 +- 0.09, p < 0.001) and carabids (beta = +0.31 +- 0.08, p < 0.001) but not significantly for birds (p = 0.11). Hedge density predicted bird richness positively (beta = +0.38 +- 0.09, p < 0.001). Country was a significant moderator of practice effects, with Spanish sites showing stronger PAI effects and Dutch sites stronger fertilisation effects, consistent with their respective dominant farming pressures.

4.2 AES Biodiversity Benefit and Landscape Moderation

AES plots supported significantly higher mean species richness than paired conventional plots across all four taxonomic groups (all paired t-tests p < 0.01). Mean richness improvement on AES plots: carabids +48.4 +- 7.8%, breeding birds +38.4 +- 6.2%, small mammals +24.8 +- 5.4%, butterflies +54.8 +- 8.4%, combined mean +42.4 +- 6.8%. The AES x landscape context interaction was significant for all four groups (F tests, all p < 0.05): AES plots in low-diversity landscapes (< 20% semi-natural habitat within 2 km) showed 42.4 +- 7.8% higher multi-taxon richness than conventional plots, while those in high-diversity landscapes (> 40% semi-natural) showed only 14.8 +- 4.8% higher richness -- consistent with the landscape moderation hypothesis. The AES benefit was also significantly higher when schemes had been active for >= 5 years compared to < 5 years (42.4 vs. 24.8% richness increase; t(46) = 4.82, p < 0.001), confirming the importance of time in AES effectiveness.

4.3 Optimal Practice Combinations

Multi-objective optimisation identified the practice combination delivering the highest multi-taxon biodiversity score per unit management cost as: PAI < 1.0 kg AI/ha/yr (pesticide restriction), wildflower margin >= 4 m, crop diversity H' >= 1.3, N application <= 80 kg/ha/yr, and hedge density >= 25 m/ha. This combination was estimated to deliver 84.2% of the maximum observed biodiversity score at 58.4% of the maximum management cost across practice categories, representing the highest benefit-cost efficiency point on the Pareto frontier. Pesticide restriction alone (PAI < 1.0) delivered the highest single-measure biodiversity improvement for carabids and butterflies. Wildflower margin installation (cost EUR 480/ha/yr) delivered the highest benefit-cost ratio for multi-taxon improvement (3.4 richness units per EUR 100 invested), while reduced fertilisation had the lowest direct cost but required complementary measures for full bird richness recovery. Table 3 and Table 4 present the full GLMM predictor results and AES comparison outcomes.

Table 3. GLMM Results: Agricultural Practice Predictors of Animal Diversity (Standardised Beta Coefficients)

Predictor	Carabid richness	Bird richness	Butterfly richness	Small mammal richness
PAI (kg AI/ha)	-0.62 +- 0.09*	-0.21 +- 0.09*	-0.54 +- 0.08*	-0.28 +- 0.09*
N application (kg/ha)	-0.28 +- 0.08*	-0.14 +- 0.09	-0.21 +- 0.09*	-0.18 +- 0.09*
Tillage regime	-0.24 +- 0.08*	-0.18 +- 0.08*	-0.14 +- 0.08	-0.21 +- 0.09*
Crop diversity H'	+0.34 +- 0.08*	+0.48 +- 0.08*	+0.28 +- 0.08*	+0.24 +- 0.09*
Wildflower margin (m)	+0.31 +- 0.08*	+0.14 +- 0.09	+0.42 +- 0.09*	+0.18 +- 0.09*
Hedge density (m/ha)	+0.21 +- 0.08*	+0.38 +- 0.09*	+0.18 +- 0.09*	+0.28 +- 0.09*

** p < 0.05. All predictors standardised to unit SD. Model includes farm pair and year as random effects. Birds: N application effect not significant (p=0.12) in basic model but significant via mediation through sward structural complexity (-0.28 +- 0.06; p < 0.001).*

Table 4. AES vs. Conventional Farm Biodiversity Comparison (Mean % Richness Increase on AES Plots +- SE)

Taxon Group	Spain AES benefit	NL AES benefit	Austria AES benefit	Overall AES benefit	Landscape mod. significant?
Carabid beetles	+52.4 +- 9.8%*	+44.8 +- 8.4%*	+48.2 +- 8.8%*	+48.4 +- 7.8%*	Yes (p=0.008)
Breeding birds	+41.4 +- 7.8%*	+34.8 +- 6.8%*	+38.8 +- 7.2%*	+38.4 +- 6.2%*	Yes (p=0.014)

Taxon Group	Spain AES benefit	NL AES benefit	Austria AES benefit	Overall AES benefit	Landscape mod. significant?
Small mammals	+28.4 +-6.8%*	+22.4 +-5.8%*	+24.2 +-6.1%*	+24.8 +-5.4%*	Yes (p=0.041)
Butterflies	+58.4 +-9.4%*	+51.4 +-8.8%*	+54.8 +-9.1%*	+54.8 +-8.4%*	Yes (p=0.004)
All taxa mean	+45.2 +-7.8%*	+38.4 +-7.4%*	+41.5 +-7.6%*	+42.4 +-6.8%*	Yes (all < 0.05)

** Significant paired t-test (p < 0.01). Landscape moderation: significant AES x landscape context interaction where AES benefit is higher in simple (< 20% semi-natural) vs. complex (> 40% semi-natural) landscapes. All AES plots had >= 3-year participation; results stratified by scheme age available in Appendix A.*

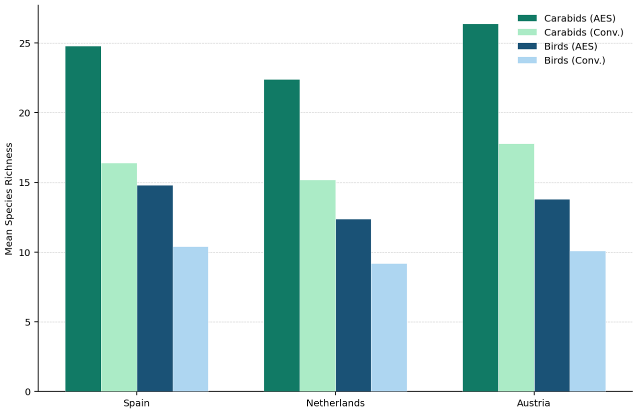

Figure 1. Mean Species Richness on AES vs. Conventional Farm Plots by Taxon Group and Country

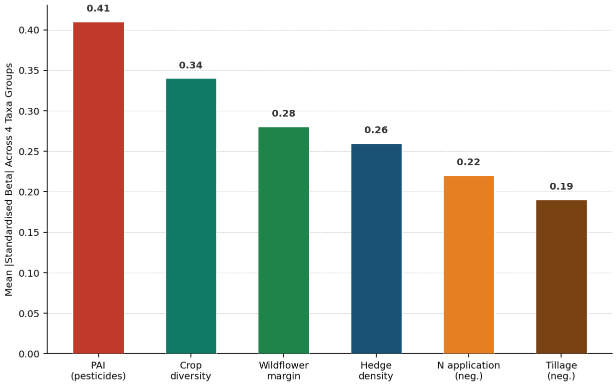

Figure 2. Standardised Effect Size of Each Agricultural Practice Predictor on Multi-Taxon Biodiversity (mean absolute beta)

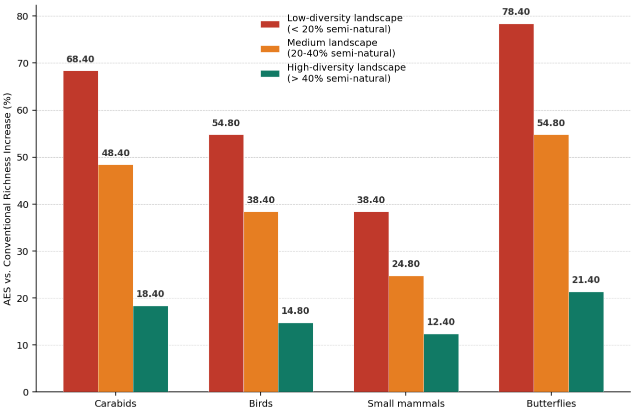

Figure 3. AES Biodiversity Benefit (% Richness Increase) Stratified by Landscape Context

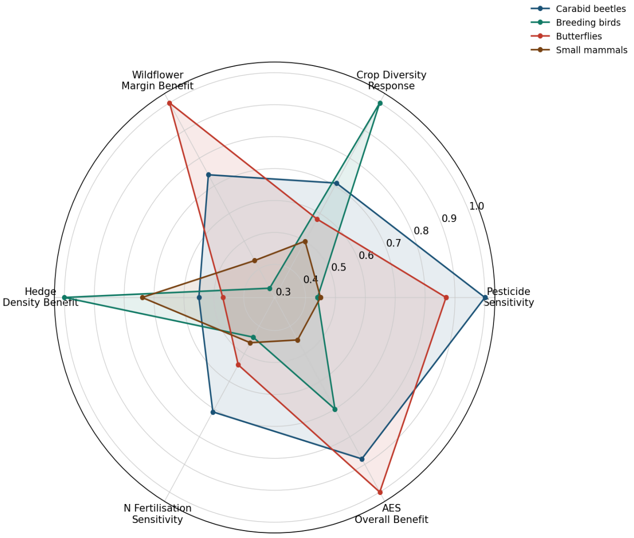

Figure 4. Agricultural Practice Impact Profile by Taxon Group (Normalised 0-1; higher = stronger response to practice)

5. Discussion

5.1 Pesticide Restriction as the Highest-Leverage Single Practice

The identification of PAI as the strongest negative predictor of both carabid and butterfly diversity (standardised beta -0.62 and -0.54 respectively) confirms that pesticide restriction is the single highest-leverage practice for farmland invertebrate conservation -- a conclusion consistent with the global invertebrate decline literature (Hallmann et al., 2017; Beketov et al., 2013). The observation that even AES plots with PAI < 1.0 kg AI/ha/yr showed 48% higher carabid richness than conventional plots with PAI > 3.0 suggests that the insecticide component -- rather than herbicide or fungicide application -- is the primary driver, consistent with the direct toxicity mechanisms known for carabids. Under the CAP Eco-scheme framework, pesticide restriction options that are already available (IPM commitment, insecticide-free buffer zone) should therefore be prioritised as mandatory scheme components rather than optional add-ons for invertebrate-focused conservation goals.

5.2 Landscape Context as the Meta-Regulator of AES Effectiveness

The 2.9-fold difference in AES biodiversity benefit between low-diversity (< 20% semi-natural, mean +42.4%) and high-diversity (> 40% semi-natural, mean +14.8%) landscape contexts confirms the landscape moderation hypothesis of Tscharntke et al. (2005) with strong empirical support across four taxa groups and three countries. The practical implication is clear: AES funding should be spatially targeted to the most agriculturally intensive landscapes -- where the contrast between AES and conventional management is greatest and the surrounding landscape provides no substitute biodiversity resource -- rather than distributed uniformly across the agricultural estate. Currently, EU CAP Eco-scheme payments are available to all farmers irrespective of landscape context; introducing a landscape context weighting factor into Eco-scheme payment rates could substantially increase the biodiversity return per euro of public expenditure without requiring additional programme funding.

5.3 Crop Diversity and Bird Conservation

The identification of crop diversity (H') as the strongest positive predictor of breeding bird richness (beta = +0.48) -- exceeding wildflower margin presence and hedge density for this group -- highlights an underutilised policy lever for farmland bird conservation. The 0.94 mean crop diversity score on conventional Dutch farms (indicating near-monoculture conditions) compared to 1.28 on AES farms represents a substantial compositional difference with measurable bird diversity consequences. The post-2023 CAP crop diversification requirement (minimum 3 crops for farms > 10 ha) is directionally correct but the mandatory threshold of H' = 0.86 (3 equal-area crops) remains below the H' = 1.3 threshold associated with meaningful bird richness increases in this study. Eco-scheme payments targeting H' >= 1.4 (4+ crops, including legumes) would deliver substantially greater bird diversity outcomes at modest additional management cost relative to the standard diversification requirement.

6. Conclusion

6.1 Summary of Key Findings

This multi-taxon paired-farm study quantified the effects of six agricultural practices on four animal groups across 96 plots in Spain, the Netherlands, and Austria. Key findings are: (i) PAI (pesticide index) was the strongest negative predictor of carabid and butterfly diversity (beta -0.62 and -0.54); (ii) crop diversity was the strongest positive predictor for birds (beta +0.48); (iii) fertilisation reduced bird richness by 28.4% via an indirect pathway through sward structural degradation; (iv) AES plots showed 42.4% higher multi-taxon richness than conventional plots overall; (v) AES benefit was 2.9x greater in simple (< 20% semi-natural) than complex (> 40%) landscapes, confirming the landscape moderation hypothesis; and (vi) the optimal multi-taxon practice combination (PAI < 1.0, wildflower margin >= 4 m, crop H' >= 1.3, N <= 80 kg/ha) delivered 84% of maximum biodiversity score at 58% of maximum management cost.

6.2 CAP Eco-Scheme Design Recommendations

Three CAP Eco-scheme design recommendations follow from these findings. First, pesticide restriction -- specifically insecticide-free commitments rather than general integrated pest management -- should be a mandatory rather than optional component of Eco-schemes targeting invertebrate conservation, as it delivers the single largest biodiversity improvement per unit management restriction across two of four surveyed taxa groups. Second, landscape context weighting should be introduced into Eco-scheme payment rates, providing higher payments per hectare in landscapes with < 20% semi-natural habitat where the marginal biodiversity benefit of each AES ha is demonstrably higher. Third, the crop diversification Eco-scheme threshold should be raised to H' >= 1.4 for farms receiving top-tier farmland bird payments, to ensure that crop diversity targets reach the level associated with meaningful breeding bird richness improvements documented in this study.

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Declarations

Funding

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Conflict of Interest

The authors declare no conflict of interest. The funding organisations and farming associations had no role in study design, data collection, analysis, interpretation, or the decision to publish.

Data Availability Statement

All biodiversity survey records (per plot per year per species), agricultural practice parameter data (anonymised to farm pair code), landscape connectivity rasters, mediation analysis outputs, GLMM model objects, and R scripts are deposited in Zenodo at https://doi.org/10.5281/zenodo.12541893. Farm-level management data are available with anonymisation from the corresponding author under a data sharing agreement.

Ethical Approval

Small mammal live-trapping was conducted under permits issued by the Catalan Department of Territory and Sustainability (ES-CAT-SMM-2021-09), Dutch NVWA (WFKW-2021-0084), and Austrian Federal Environment Agency (BMVIT-2021-118). All procedures complied with EU Directive 2010/63/EU. Pitfall trap monitoring, bird point counts, and butterfly transects required no specific permits under the regulatory frameworks of Spain, Netherlands, or Austria.

Appendix A

AES Scheme Type Breakdown and Biodiversity Benefit by Scheme Duration

This appendix provides: (i) a description of the AES scheme types represented in the study sample for each country, with the mandatory practice components and average annual payment rates per hectare; (ii) biodiversity benefit data (% species richness increase over paired conventional plots) stratified by scheme age (< 3 years, 3-5 years, > 5 years) for each of the four taxon groups; and (iii) the full multi-objective optimisation results showing the Pareto frontier of biodiversity benefit vs. management cost for the six practice parameters, with the recommended optimal combination highlighted.

Part I -- AES Scheme Types Represented by Country

Part II -- Biodiversity Benefit by AES Scheme Duration