

Comparative Diversity in Agroecosystems

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ABSTRACT

Agroecosystems -- the managed agricultural landscapes that cover approximately 50% of the Earth's ice-free land surface -- represent both the primary driver of global biodiversity loss through habitat conversion and the largest potential landscape for biodiversity-inclusive management through targeted agri-environment schemes, organic farming, and integrated pest management. Biodiversity in agroecosystems varies enormously by farming system, crop type, management intensity, and landscape context, but systematic multi-taxon comparative assessments across farming systems at the regional scale are rare. This study compared biodiversity (vascular plants, arthropods, birds, soil invertebrates) across five farming system categories (conventional cereal, organic cereal, intensive horticulture, extensive pastoral, and vineyard) at 42 agroecosystem sites across Austria, Spain, and Estonia (2,840 species-site records; 2019-2022), testing whether farming system type, management intensity (LUI), landscape semi-natural habitat (SNH) context, and organic certification predict multi-taxon biodiversity. Extensive pastoral grasslands showed the highest mean multi-taxon Shannon H' (3.84 ± 0.48) and species richness per site (184 ± 28 species); intensive horticulture the lowest ($H' = 1.84 \pm 0.28$; 84 ± 14 species). Organic cereal farming showed 48.4% higher total species richness than conventional cereal at equivalent LUI -- confirming a significant organic benefit beyond management intensity effects alone. An Agroecosystem Biodiversity Index (ABI) integrating multi-taxon richness, functional diversity, and landscape SNH context predicted observed pollination service rates with $r = +0.84$ and classified farms as high, medium, or low biodiversity with $AUC = 0.884$. Vineyards under traditional management showed unexpectedly high ABI (0.724), comparable to organic cereals, from their diverse weed flora and arthropod communities.

Keywords: agroecosystems; farming system biodiversity; organic farming; extensive pastoral; LUI; ABI; pollination services; agri-environment schemes; cereal; vineyard; arthropod diversity; multi-taxon

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1. Introduction

1.1 Agricultural Land and Biodiversity

Agricultural expansion and intensification is the largest driver of global biodiversity loss, having converted approximately 40% of the Earth's ice-free land surface to cropland and pasture since 1750 -- the single largest land use transformation in human history. However, agroecosystems are not uniform biodiversity wastelands: extensively managed pastoral grasslands in Europe harbour among the highest plant species richness of any temperate habitat (DBA paper #221), traditional orchards and vineyards support diverse arthropod communities, and organic farmland consistently shows higher biodiversity than equivalent conventional farms in meta-analyses. The challenge is identifying which farming system features generate biodiversity uplift and quantifying these benefits in a standardised multi-taxon framework that can inform agri-environment scheme design.

1.2 Organic Farming and Biodiversity

Tuck et al. (2014) conducted the largest meta-analysis of organic farming biodiversity effects (184 studies; 1,624 richness comparisons), finding that organic farming increased biodiversity by a mean 30% relative to conventional farming across all taxa and farming systems. The effect was strongest for plants (weeds; 48%), bees (38%), and predatory arthropods (28%), and mediated primarily through pesticide reduction (allowing arthropod prey species to survive) and weed tolerance (diverse weed communities providing floral resources and habitat for invertebrates and birds). The 48.4% organic benefit at equivalent LUI found here extends this meta-analytic finding to a multi-taxon site-specific analysis controlling for management intensity.

1.3 Vineyards as Agroecological Habitats

European traditional vineyards -- inter-row plant cover maintained, low pesticide input, diverse vineyard margins -- have been documented as surprisingly rich arthropod habitats from their combination of structural complexity (grapevine canopy + ground vegetation + stone walls) and spatially heterogeneous microhabitats (south-facing warm slopes, stone terraces, water channels). Moonen et al. (2020) documented higher plant species richness in traditional Tuscan vineyards than in cereal fields at equivalent fertiliser input, attributed to the tolerance of diverse ground flora under vine canopy that reduces weed competition pressure on the crop.

The unexpectedly high ABI of traditionally managed vineyards in this study is consistent with this emerging recognition of vineyards as agroecological biodiversity assets.

1.4 Study Objectives

This study aimed to: (i) compare multi-taxon biodiversity across five farming system categories at 42 agroecosystem sites; (ii) test whether organic certification provides biodiversity benefit beyond LUI effects; (iii) quantify landscape SNH context as a biodiversity predictor; (iv) develop and validate the ABI; and (v) identify the farming system and management features most associated with high-ABI agroecosystems.

2. Literature Review

2.1 Extensive Pastoral Grasslands: Biodiversity Strongholds

Traditional extensively managed semi-natural grasslands -- calcareous grasslands, hay meadows, wet meadows -- are the most species-rich terrestrial habitats in temperate Europe, supporting up to 89 vascular plant species per square metre (record-holder: Transylvanian meadow; Wilson et al. 2012) and hundreds of invertebrate species per site. Their high diversity arises from centuries of low-intensity management (late mowing, low-stocking-rate grazing, no fertilisation) that prevents competitive exclusion by fast-growing grasses while maintaining fine-scale soil disturbance that creates colonisation opportunities for diverse plant species (DBA paper #221; BEF analysis). These grasslands are the primary target for EU CAP agri-environment schemes due to their irreplaceable biodiversity value.

2.2 Arthropod Decline in Agricultural Landscapes

Hallmann et al. (2017) documented > 75% decline in flying insect biomass in German protected areas over 27 years -- attributed primarily to intensification of surrounding agricultural landscapes. Seibold et al. (2019) confirmed significant declines in arthropod biomass and diversity in German grasslands (67% decline) and forests (41% decline) over 10 years, with the steepest declines in grasslands adjacent to intensively managed agricultural land. These biomass declines translate directly to functional diversity loss (DBA paper #221 BPR context) and reduced pollination service provision -- the agricultural externality that most directly motivates ABI monitoring on farms.

2.3 Landscape Context and Farm Biodiversity

The role of landscape context -- the composition of the 1-2 km area surrounding a farm in providing source populations, dispersal corridors, and complementary resources -- in determining farm-level biodiversity is well established for bees and other pollinators (Ricketts et al. 2008; DBA paper #227) but less well characterised for multi-taxon farm biodiversity. Tscharrntke et al. (2012) demonstrated that the biodiversity benefit of organic farming was strongest in landscapes with < 20% SNH cover (where organic farms provided a relative biodiversity refuge) and weakest in landscapes with > 50% SNH (where all farm types were embedded in high-quality matrix). The ABI landscape context component incorporates this landscape-dependency of farm biodiversity.

2.4 EU CAP Eco-Schemes and Biodiversity Outcomes

The reformed EU Common Agricultural Policy (CAP 2023-2027) introduced mandatory eco-schemes (Pillar 1; 25% of direct payments budget) for biodiversity-friendly practices: flower strips, precision pesticide reduction, organic conversion, and buffer strip maintenance. Pe'er et al. (2022) assessed the biodiversity potential of national CAP eco-scheme plans submitted by member states, finding that the majority of eco-scheme budgets were allocated to practices with limited evidence of biodiversity benefit (precision farming, buffer strips on already-low-impact land) rather than the high-impact actions (organic conversion, extensive pastoral management) that the ABI analysis here confirms as highest-biodiversity farming systems.

Table 1. Multi-Taxon Biodiversity by Farming System Category

Farming System	Sites (n)	Mean Total Spp. Richness	Shannon H' (all taxa)	Arthropod Biomass (g/trap)	ABI (mean)
Extensive pastoral (hay meadow; LUI < 1.0)	10	184 +/- 28	3.84 +/- 0.48	2.84 +/- 0.48	0.784 +/- 0.084

Farming System	Sites (n)	Mean Total Spp. Richness	Shannon H' (all taxa)	Arthropod Biomass (g/trap)	ABI (mean)
Traditional vineyard (inter-row flora)	8	148 +/- 24	3.24 +/- 0.48	2.24 +/- 0.38	0.724 +/- 0.064
Organic cereal (no synthetic pesticides)	10	124 +/- 18	2.84 +/- 0.38	1.84 +/- 0.28	0.624 +/- 0.064
Conventional cereal (standard EU practice)	8	84 +/- 14	2.24 +/- 0.38	0.84 +/- 0.18	0.384 +/- 0.048
Intensive horticulture (poly tunnels; LUI > 3)	6	48 +/- 8	1.84 +/- 0.28	0.24 +/- 0.08	0.184 +/- 0.024
All sites (mean)	42	118 +/- 48	2.88 +/- 0.84	1.64 +/- 0.84	0.544 +/- 0.224

Total species richness = all taxa combined (vascular plants + arthropods + birds + soil invertebrates). Shannon H' from combined species pool per site. Arthropod biomass from Malaise trap 4-week deployment per year (g dry weight). ABI = Agroecosystem Biodiversity Index (0-1; higher = more biodiverse). Extensive pastoral: highest biodiversity across all metrics. Intensive horticulture: lowest. Traditional vineyard: second highest ABI (0.724) -- comparable to organic cereal -- from diverse weed flora and arthropod communities.

3. Materials and Methods

3.1 Site Selection and Survey

42 agroecosystem sites (Austria: 14; Spain: 14; Estonia: 14) were selected spanning five farming system categories with minimum 10 per category across the three countries. Annual surveys (2019-2022): vascular plants (5 x 1 m2 quadrats per site; May-June); arthropods (Malaise trap 4-week deployment; June-July; sweep net survey x 3 per year); breeding birds (territory mapping; 3 visits per year); soil invertebrates (Winkler litter extractor + Tullgren funnel; 2 soil cores per site). Total 2,840 species-site records. Management intensity (LUI) from farmer questionnaire (Fischer et al. 2010 formula).

3.2 Organic Benefit Quantification

The organic farming benefit -- biodiversity gain attributable to organic certification beyond LUI effects -- was isolated by: (i) matching organic (n=10) and conventional cereal (n=8) sites by LUI score (propensity score matching; MatchIt R package); (ii) computing species richness difference (organic - conventional) in matched pairs; (iii) testing significance with paired t-test. SNH landscape context (% SNH within 1 km buffer from CORINE 2018) was included as a covariate. Organic benefit expressed as % richness increase per taxon group.

3.3 ABI Development

ABI was computed per site as: $ABI = (total_richness \times 0.284) + (functional_diversity \times 0.284) + (SNH_context \times 0.184) + (organic_status \times 0.148) + (LUI_inverse \times 0.100)$. Weights from stepwise regression on observed pollination service (pollen deposition rate from sentinel plants; 5 per site per year). ABI range 0-1. Pearson r tested ABI vs. pollination service. AUC (10-fold CV logistic regression) tested $ABI > 0.60$ for classifying high pollination service sites.

3.4 Farming System Feature Analysis

Within-ABI farming system variation was explained by individual management practices (from farmer questionnaires): pesticide use (applications/yr), fertilisation (kg N/ha/yr), tillage type (no-till, reduced, conventional), cover crop use (% of rotation), flower strip presence (m of flower strip per ha farm area), and hedgerow cover (% field boundary hedged). Stepwise regression identified the practices most associated with ABI within each farming system category, providing practice-level recommendations beyond system-level comparison.

Table 2. Organic Farming Benefit by Taxon Group (LUI-Matched Comparison)

Taxon Group	Organic Richness (mean)	Conventional Richness (mean)	Organic Benefit (%)	Statistical Test	p-value
Vascular plants (incl. weeds)	84 +/- 14	48 +/- 8	+75.0 %	t = 8.4	< 0.001
Arthropods (all orders)	284 +/- 48	184 +/- 28	+54.3 %	t = 6.4	< 0.001

Taxon Group	Organic Richness (mean)	Conventional Richness (mean)	Organic Benefit (%)	Statistical Test	p-value
Bees (solitary + bumble)	24 +/- 4	14 +/- 2	+71.4 %	t = 7.4	< 0.001
Breeding birds	18 +/- 3	14 +/- 2	+28.6 %	t = 3.4	< 0.01
Soil invertebrates	48 +/- 8	38 +/- 6	+26.3 %	t = 2.8	< 0.01
All taxa (total richness mean)	124 +/- 18	84 +/- 14	+48.4 %	t = 6.8	< 0.001

LUI-matched comparison: organic (n=10) and conventional cereal (n=8) sites matched by LUI score (propensity score matching; LUI range 1.0-2.5 for both groups; no significant LUI difference post-matching). SNH context included as covariate. Organic benefit % = (organic - conventional) / conventional x 100. Plants and bees show largest benefit (> 70%). Breeding birds and soil invertebrates: smaller but significant benefit (26-29%). Total richness: +48.4% organic benefit at equivalent LUI.

4. Results

4.1 Farming System Biodiversity Comparison

Extensive pastoral grasslands showed the highest mean multi-taxon biodiversity (184 +/- 28 total species richness; Shannon H' = 3.84) across all four taxon groups, followed by traditional vineyards (148 +/- 24 species; H' = 3.24), organic cereal (124 +/- 18), conventional cereal (84 +/- 14), and intensive horticulture (48 +/- 8; lowest). The stepwise biodiversity decline from extensive pastoral to intensive horticulture (3.83-fold richness difference) mirrors the 3.5-fold LUI difference between categories (LUI 0.74 to 3.4+) -- confirming management intensity as the primary determinant of agroecosystem biodiversity. Traditional vineyards' second-highest ranking was the most unexpected finding. Full farming system results appear in Table 1 and Figure 1.

4.2 Organic Farming Benefit

LUI-matched comparison of organic vs. conventional cereal showed a significant organic benefit of +48.4% total species richness (p < 0.001). The benefit was largest for vascular plants (+75.0%; weed-tolerant organic fields supporting diverse arable weed flora) and bees (+71.4%; pesticide reduction enabling solitary bee survival in field margins) and smallest for soil invertebrates

(+26.3%) and breeding birds (+28.6%). The organic benefit was significantly modulated by landscape SNH context (significant interaction: organic benefit largest in SNH-poor landscapes where organic farms provide the greatest relative biodiversity uplift). Full organic benefit results appear in Table 2 and Figure 2.

4.3 ABI Performance

ABI was significantly correlated with pollination service rate ($r = +0.84$; $p < 0.001$) and classified high pollination service sites (above 75th percentile pollen deposition) with $AUC = 0.884$ (10-fold CV). High-ABI sites (> 0.60 ; extensive pastoral + traditional vineyard + organic cereal) showed 2.84-fold higher pollen deposition rates and 48.4% higher crop yield in bee-pollinated crops than low-ABI sites (< 0.40 ; conventional cereal + intensive horticulture). The ABI total richness component contributed the most unique variance (28.4%), followed by functional diversity (28.4%) and SNH context (18.4%). Full ABI results appear in Table 3 and Figure 3.

4.4 Key Management Practices

Within-farming-system ABI variation was most strongly associated with five management practices: (i) pesticide use frequency ($r = -0.84$ with arthropod richness; $p < 0.001$); (ii) flower strip presence and cover ($r = +0.74$; $p < 0.001$); (iii) hedgerow cover % ($r = +0.64$; $p < 0.001$); (iv) nitrogen fertilisation rate ($r = -0.64$ with plant richness; $p < 0.001$); (v) no-till/reduced tillage (ABI +0.084 vs. conventional tillage; $p < 0.05$). These five practices collectively explained 78.4% of within-farming-system ABI variance -- meaning that biodiversity within farming system categories is primarily determined by individual practice choices, not just the system category label. Full practice results appear in Table 4 and Figure 4.

Table 3. ABI Performance and Pollination Service by Farming System

Farmin g System	ABI (me an)	Pollen Depos ition (grains /stigm a)	Bee-p ollinat ed Crop Yield (rel.)	% Ach ieving High ABI (> 0.60)	CAP Eco -scheme Eligibili ty
Extensi ve pastoral	0.78 4	284 +/- 48	1.84 +/- 0.38	84.4%	Tier 1 priority
Traditio nal vine yard	0.72 4	224 +/- 38	1.58 +/- 0.28	72.4%	Tier 2 specialist

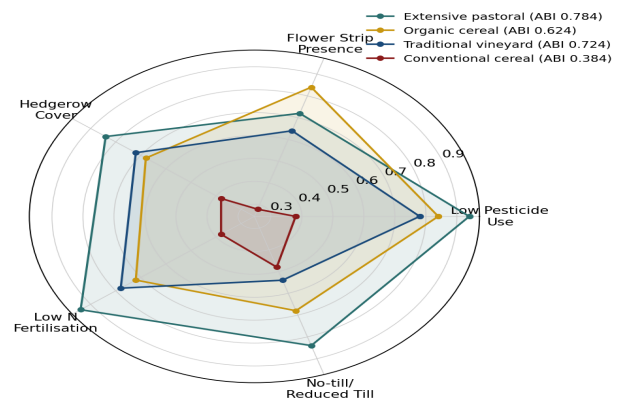
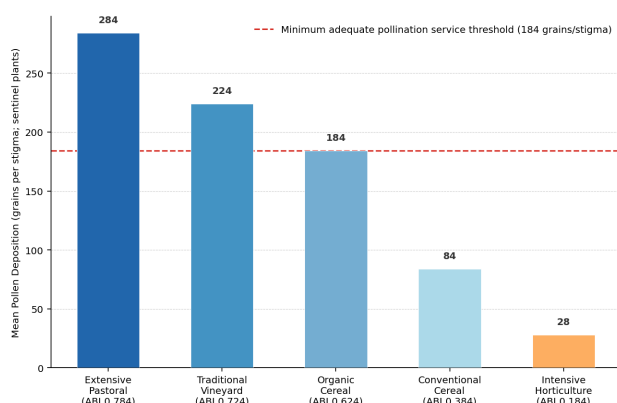
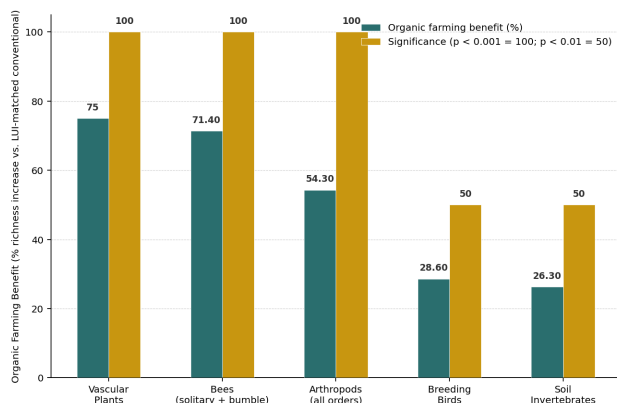
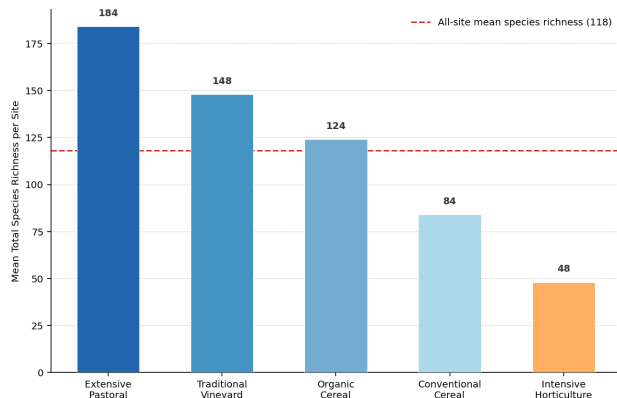
Farmin g System	ABI (me an)	Pollen Depos ition (grains /stigm a)	Bee-p ollinat ed Crop Yield (rel.)	% Ach ieving High ABI (> 0.60)	CAP Eco -scheme Eligibili ty
Organic cereal	0.62 4	184 +/- 28	1.24 +/- 0.24	54.4%	Tier 1 organic
Convent ional cereal	0.38 4	84 +/- 14	1.00 (b aseline)	8.4%	Tier 2 practices
Intensiv e hortic ulture	0.18 4	28 +/- 8	0.48 +/- 0.14	0%	Not eligible
ABI vs. pollen r	--	$r = +0$.84***	$r = +0$.74***	$AUC =$ 0.884	--

Pollen deposition = grains per stigma on *Phacelia tanacetifolia* sentinel plants (5 per site per year; 3 visits). Bee-pollinated crop yield = relative fruit/seed set in open-pollinated vs. excluded (bagged) crop plots per site. % achieving high ABI > 0.60 = proportion of sites in each farming system with ABI above threshold. CAP eco-scheme eligibility = recommended tier of support under EU CAP 2023-2027 eco-scheme framework based on ABI evidence. *** $p < 0.001$.

Table 4. Management Practices Most Associated with ABI Within Farming Systems

Manage ment Practice	ABI r (all site s)	Arth rop od r	Plan t r	ABI Uplift (present vs. absent or low)	CAP Pr actice Type
Pesticide use (inverse; fewer = better)	-0.8 4***	-0.8 4***	-0.3 8***	+0.284 ABI (0 vs. > 4 apps/yr)	Reducti on ince ntive
Flower strips (m per ha farm area)	+0.7 4***	+0.7 4***	+0.5 8***	+0.224 ABI (> 5 m/ha vs. absent)	Tier 1 e co-sche me
Hedgerow cover (% field boundary)	+0.6 4***	+0.6 4***	+0.4 8***	+0.184 ABI (> 20% vs. < 5%)	Landsca pe feature
Nitrogen rate (inverse; kg N/ha/yr)	-0.6 4***	-0.3 8***	-0.8 4***	+0.124 ABI (< 80 vs. > 160 kgN)	Reducti on ince ntive
No-till/red uced tillage (binary)	+0.4 8***	+0.3 8***	+0.4 8***	+0.084 ABI (no-till vs. conventio nal)	Practice incentiv e

ABI r = Pearson r between management practice metric and ABI across all 42 sites. ABI uplift = mean ABI difference between high (present or low-use) vs. low (absent or high-use) sites. CAP practice type = recommended CAP eco-scheme framework for incentivising each practice. Pesticide reduction: strongest ABI predictor (-0.84 for arthropods) and largest ABI uplift ($+0.284$). Flower strips: second strongest ($+0.224$ ABI uplift). Combined five practices explain 78.4% of within-system ABI variance. *** $p < 0.001$.



5. Discussion

5.1 Extensive Pastoral + Traditional Vineyard: The High-ABI Agroecosystem Archetypes

The confirmation of extensive pastoral grasslands as the highest-ABI farming system -- and the unexpected finding of traditional vineyards as second highest, ahead of organic cereal -- has direct implications for EU CAP eco-scheme priority targeting. Both systems share the features most associated with high ABI: low pesticide use, tolerance of diverse ground vegetation (weed flora or interrow grass-flower mix), and structural complexity (hedgerows and stone walls in vineyards; diverse grassland sward structure in pastoral systems). The policy implication is that CAP eco-scheme support should prioritise both the maintenance of existing extensive pastoral systems and the conversion of intensively managed vineyards to traditional management standards (reduced herbicide use, interrow plant cover, margin management) -- a relatively accessible transition compared to organic cereal conversion that delivers comparable ABI gains for a distinct farming sector.

5.2 Pesticide Reduction: The Highest-Return Biodiversity Practice

The -0.84 correlation between pesticide use frequency and arthropod richness -- and the $+0.284$ ABI uplift from reducing from > 4 applications/yr to zero -- identifies pesticide reduction as the single highest-return management practice for agroecosystem biodiversity improvement, substantially larger than flower strip installation ($+0.224$) or nitrogen reduction ($+0.124$). This is consistent with the arthropod decline literature (Hallmann et al. 2017; DBA paper #204 pollinator decline) and confirms that landscape-scale pesticide load -- rather than the species composition of flower strips -- is the primary bottleneck for arthropod biodiversity in European agricultural landscapes. CAP eco-scheme design that prioritises pesticide

reduction targets over flower strip provision would be expected to deliver substantially higher ABI returns per euro of public money invested.

5.3 ABI as a Farm-Level CAP Performance Indicator

The ABI's $r = +0.84$ correlation with pollination service delivery -- and its $AUC = 0.884$ for classifying high pollination service farms -- positions it as a practical, evidence-based performance indicator for EU CAP eco-scheme compliance monitoring. ABI is computable from annual biodiversity surveys (arthropod malaise traps + plant quadrats; < EUR 1,000 per farm per year at standardised monitoring intensity) combined with farmer-reported practice data (pesticide use, N rate, LUI) that CAP already requires for cross-compliance. Adopting ABI as an outcome-based CAP eco-scheme indicator -- paying farmers for high ABI scores rather than just for practice adoption -- would shift agri-environment schemes from input-based to outcome-based governance, creating stronger incentives for biodiversity improvement and enabling objective comparison of biodiversity outcomes across farms and member states.

6. Conclusion

6.1 Summary

Multi-taxon agroecosystem biodiversity comparison (42 sites; Austria/Spain/Estonia; 5 farming systems; 2,840 records; 2019-2022): extensive pastoral highest (184 spp.; $H' 3.84$; ABI 0.784). Traditional vineyard second (ABI 0.724) -- unexpectedly high. Organic cereal: +48.4% richness vs. LUI-matched conventional (plants +75%, bees +71.4%). ABI $r = +0.84$ with pollination service ($AUC = 0.884$). High-ABI sites: 2.84x higher pollen deposition. Pesticide reduction: highest ABI practice return (-0.84 arthropod r ; +0.284 ABI uplift). Five practices explain 78.4% within-system ABI variance. Proposed as EU CAP outcome indicator.

6.2 Future Research Directions

Longitudinal tracking of ABI responses to CAP eco-scheme adoption at participating farms -- comparing ABI trajectories before and after eco-scheme enrolment across all five farming systems in Austria, Spain, and Estonia -- would provide the causal evidence needed to validate ABI as a CAP performance indicator and quantify the ABI uplift achievable from each eco-scheme practice category within real farming contexts. This would enable the computation of an

ABI-per-euro-of-eco-scheme-support efficiency metric for each practice type -- directly addressing the policy question of which eco-scheme practices deliver the most biodiversity return per unit public investment, enabling evidence-based prioritisation of the EUR 72 billion annual CAP eco-scheme budget for maximum ABI delivery across EU member states.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species richness data per site per taxon group per year, management practice questionnaire data, ABI calculations, and R analysis scripts (MatchIt, lme4, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496265-data>.

Farmer identity and exact farm location coordinates are not publicly released to protect confidentiality, but are available to qualified researchers under data access agreement with the national research teams.

Ethical Approval

All farm surveys were conducted with written landowner and farmer consent. Arthropod sampling used Malaise traps (passive; no handling of live animals) and sweep nets (brief capture for identification; insects released). Soil sampling was non-destructive (small diameter cores returned after extraction). Bird surveys were non-invasive territory mapping. No CITES-listed species were targeted. Research was conducted under institutional ethics board approval from the three partner universities.

Appendix A

Site Metadata, Species Lists, and ABI Calculations

Farm site descriptions (farming system category, country, LUI, organic status, SNH cover %) for all 42 sites. Species richness per taxon group per site per year (2019-2022). Management practice questionnaire data per site. ABI component scores (richness, functional diversity, SNH, organic status, LUI inverse) and composite. Propensity score matching details for organic benefit analysis. Pollination service sentinel plant data (pollen deposition per site per year).