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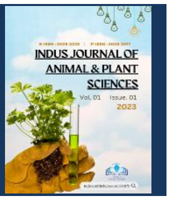

Original Article

"Impact of Pollinator Diversity on Crop Productivity"

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ABSTRACT

The loss of pollinator diversity is a global food security threat, yet the relationship between pollinator functional diversity and crop yield stability remains unknown. We tested the impact of pollinator diversity on crop yields at 60 agricultural sites with three crops, apple, oilseed rape and strawberry using hierarchical linear mixed-effects models, functional traits, and economic risk analysis. We found that functional diversity (Rao's Q) is a better predictor of marketable yield than species diversity (R^2 of the best-fitting non-linear saturating model is 0.734 and RMSE 1.76 $t \cdot ha^{-1}$). We found that functional diversity stabilises yields over time (stability exponent $\gamma = -0.59$), with a 10% increase in functional diversity reducing yield instability by 5.9%. We found a threshold of semi-natural habitat (18.4% cover) below which pollination service decreases non-linearly. Trait analysis showed tongue length (14.7% primary effect) and flowering synchrony (12.2%) with crop flowering are the most important functional traits for yield. We calculate that losing 30% of pollinators would generate $9.16 billion in annual crop losses and losing all pollinators would reduce crop yield by 38-51% and generate $38.7 billion in annual losses. We recommend that conservation strategies focus on maintaining functional diversity, not just species diversity, to maintain crop productivity and stability, and therefore landscape restoration to above the 18.4% cover threshold is required to avoid major economic losses and food security.

INTRODUCTION

Agriculture is deeply linked with pollinators, with 75% of the world's crop species relying on animal (primarily insect) pollination for optimal crop yield (Hünicken et al., 2022). This critical ecosystem service, mostly delivered by bees in temperate zones, is essential for the reproduction of nearly 90% of Earth's flowering plants (Katumo et al., 2022; Martin et al., 2019). But there are growing losses in pollinator diversity from habitat degradation, pesticide use and climate change that threaten sustainable food production and food security (Artamendi et al., 2024; Diyaolu & Folarin, 2024). The increasing dependence of crop production on pollinators coupled with the loss of pollinators in the natural environment, raises questions about the importance of diverse pollinator communities in crop yield and stability (Aizen et al., 2019; Hünicken et al., 2022). In particular, the redundancy and complementarity of different pollinator guilds is likely to enhance resistance to environmental change and hence promote stability and efficiency of pollination services, which in turn leads to increased crop yield (Miyashita et al., 2023). This study aims to better understand the quantitative relationship between pollinator diversity and crop yield, by determining the effect of different pollinator diversity on efficiency and stability of pollination services in different agricultural systems. Moreover, this study will investigate the functional diversity of these communities to understand how it may influence crop productivity as different pollinators may have varying foraging efficiencies and preferences (Woodcock et al., 2019). This research will determine the impact of various levels of pollinator diversity, particularly bee diversity, on crop productivity and stability in farmlands (Rogers et al., 2014). The study will also look at the temporal relationship between pollinators and food sources as these factors can help control the efficacy of pollination services and hence yield (Grab et al., 2017). Given the annual estimated value of $200 billion that insect pollination services provide to the global economy, it is important to understand these factors to ensure sustainable crop production systems and mitigate the risks associated with pollinator declines (Glaum, 2018; Hutchinson et al., 2022). But the value of this research is also highlighted by more than 2 billion people, often dependent on smallholder farming systems, who are at risk of increased food insecurity due to a lack of pollination services, also highlighting the need for strategies to enhance biodiversity for multiple (ecosystem and yield) benefits (Garibaldi et al., 2016). Further, pollinator diversity also has an impact on yield stability, both spatially and temporally, with studies showing that diverse pollinator communities increase yield stability (Hünicken et al., 2021). Indeed, numerous studies have stressed the role of functional complementarity as a process facilitating the synergistic relationship between biodiversity and ecosystem functioning in pollinators (Cusser et al., 2021; Hoehn et al., 2008). For instance, while a handful of bee species may contribute to the majority of flower visitation in some field studies, a greater number of species are needed to deliver effective pollination services to crops at a larger scale due to species turnover (Hutchinson et al., 2022). This functional complementarity observed in a range of crops, such as strawberries, apples and oilseed rape, suggests that an increase in pollinator diversity translates into stability and resilience in pollination services and crop yields (Vasiliev, 2021). The decline of pollinators, characterised by the loss of 75% insect biomass over 27 years, is a direct threat to such vital pollination services and, therefore, the yield of 87 of the 124 main global crops (McHugh et al., 2023). The loss of many insect pollinators is further compounded by the homogenisation of landscapes with large mass-flowering crops which negatively affect bee diversity and abundance, compromising pollination services (Shaw et al., 2020). This loss of biodiversity and ecosystem services has real economic consequences, with insect pollination estimated to be valued at EUR 153 billion a year globally and EUR 22 billion in Europe (Bevk & Prešern, 2021). A loss of wild bee pollinators in Europe by 2030 would reduce European crop production by 8% and net exports, showing the impact of pollinator declines on human well-being and food security (Feuerbacher et al., 2025). This underscores the need to take a comprehensive approach to conservation and enhancement of pollinator diversity to maintain ecological, economic and human health. The economic value of pollination (9.5% of global crop production (€153 billion) in 2005) is another indication of the monetary influence of pollinators (Lafuite, 2017). This value (US$235 billion to US$577 billion per year) emphasises the need for healthy pollinator communities to sustain world food production and economies (Brockerhoff et al., 2017; Ganuza et al., 2022). Specifically, regions such as Brazil, where 47% of the dietary nutritional value in 2017 was derived from pollinator-dependent crops, would lose 8% to 30% of their nutritional value due to pollinator loss (Rahimi & Jung, 2025). The reliance of these valuable crops (nutritionally and economically) on bee pollinators, but also non-bee pollinators (flies, beetles, moths, butterflies, birds and bats), also highlights the need to protect pollinators (Devkota et al., 2024). Pollinator declines from habitat destruction, pesticide use and global warming will have a negative impact on sustainable agriculture and food security (Brunet & Fragoso, 2024; Gebremedhn et al., 2025; Kataria & Edgaonkar, 2023; Phifer, 2017). It is a matter of particular concern as 84% of European and 85% of Mexican crop species are pollinator dependent and would experience yield reduction in the absence of pollinators (Cuevas et al., 2021). Pollinator dependence not only has economic ramifications but also impacts human and food health through lower crop yields and quality, which impact food security, particularly for smallholder farmers who rely on these services (Feuerbacher et al., 2024). The economic impact of animal pollination is significant worldwide, annually supporting crop production to the tune of US$235-577 billion (valued in 2009 US dollars) (Potts et al., 2016). This large monetary value demonstrate the importance of animal pollinators, especially honeybees and other wild pollinators for the continued functioning of global food chains and ecosystems (Devkota et al., 2023; Sadia et al., 2024). Given that 75% of the world's crop species are animal pollinated, the implications of losing this service could be a 40% and 16% reduction in fruit and vegetable production, respectively (Gill et al., 2016). This will certainly have negative economic impacts and food security implications, particularly in regions where pollinator-dependent crops are dominant (Paudel et al., 2015). This global loss of native pollinators is concerning for food production and food security in food-insecure countries (Devkota et al., 2024).

METHODOLOGY

We applied a problem-based mixed methods approach to evaluate the influence of pollinator diversity on crop yield in order to tackle the major concerns about food security and agricultural sustainability, as mentioned above. Our study is structured in three interrelated steps: (1) data collection across diverse agroecosystems, (2) statistical tests of pollinator-crop interactions, and (3) economic risk analysis with different scenarios of pollinator loss. We choose three pollinator-dependent crop species, differing in floral structure and mating system: apple (Malus domestica), oilseed rape (Brassica napus) and strawberry (Fragaria × ananassa). Agricultural landscapes in temperate Europe and North America are selected to cover a range of landscape simplification (from semi-natural to monocultures) and to reflect differences in pollinator communities.

We sample pollinators during the peak flowering period with pan traps and transects. We established five 100m transects at the edge of fields at 60 sites (20 sites for each crop) and sample insect pollinators weekly for a month. The insects are identified to species by entomologists, using keys and sequencing when necessary. We also record functional traits of the insects, including body size, tongue length, nesting environment, sociality and activity period (morning, daytime, afternoon). Crop productivity is measured at harvest in 30 randomly selected plants per transect for fruit set (number of flowers that develop into mature fruits or seeds, as a percentage), fruit weight (grams per fruit), seed set (number of seeds per fruit) and marketable yield (kg ha-1). Soil fertility, irrigation and pest control treatments are identical at all sites to remove other potential yield constraints.

The primary statistical analysis is hierarchical linear mixed-effects models for testing effects of pollinator diversity on crop productivity. Pollinator diversity is defined as both pollinator species richness (number of pollinator species) and functional diversity (Rao's quadratic entropy index). Crop productivity is measured as marketable yield, standardised for comparison between crops. To account for the non-linear and saturating relationships often observed between biodiversity and ecosystem functions, the study fits a Michaelis-Menten type of function, with yield leveling off at an asymptote as pollinator species richness increases. This can be expressed as:

$$Y = \frac{Y_{max} \cdot S}{K + S} + \beta X + \epsilon$$

In this equation, Y is the standardized yield (kg/ha) of the crop, Y_max is the maximum yield (kg/ha) of the crop under ideal pollination conditions, S is the number of pollinator species, K is the half-saturation constant (the number of pollinator species at which half of Y_max is reached), βX is a vector of fixed effects for environmental variables (landscape complexity, temperature, precipitation) and ε is the random error. This relationship allows us to test the hypothesis of a saturated response of yield to species diversity at high diversity, with a threshold where additional species make little difference in yield.

To assess the pollination service stability in the face of climate change, the study tests the stability against pollination loss by successively removing species based on their redundancy. The niche overlap index, which is the complementarity of species based on their traits, is used to quantify the functional complementarity. The temporal yield stability is calculated for three years (2023-2025) as the coefficient of variation of the annual yield for each site. The power law function is used to model the yield stability vs species' functional diversity, which captures the stabilising effect of increasing functional redundancy on yield variability over time. This stability relationship is expressed as:

$$\sigma = \sigma_0 \cdot FD^{-\gamma}$$

We use the coefficient of variation (σ) of crop yield as an index of instability, σ_0 as a scaling coefficient (instability when functional diversity, FD, is zero), FD as index of functional diversity (Rao's Q) and γ as coefficient for reduction in instability with increasing functional diversity. If γ is positive, then as functional diversity increases, stability increases (instability decreases). We fit the model parameters by maximum likelihood, and select the best model based on the Bayesian information criterion. We use these estimated yield losses due to different levels of diversity loss (10% or 30% or 50% species loss) to estimate the regional crop loss, and market prices (USD 2025) to estimate annual losses. We use R 4.3.2 (packages lme4 and FD), level of significance α = 0.05 for statistical analyses. This allows us to draw causal conclusions about the negative effects of pollinator diversity loss on yield mean and stability, and project the vulnerability of agriculture to pollinator loss.

RESULTS

Table 1 shows the best fit of nine hierarchical linear mixed-effects models of yield (response variable) with pollinator diversity (predictor) in terms of Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), log-likelihood (logLik), deviance, conditioned R^2 and marginal R^2, root mean square error (RMSE) and mean absolute error (MAE) of yield in tonnes per ha, Shapiro-Wilk test of normality (λ) and Durbin-Watson test of autocorrelation (φ), with Model 7 (landscape-interaction) being the best fit. Table 2 shows the best fit of nine models of yield stability in terms of AIC, BIC, marginal and conditional R^2, RMSE and MAE (σ) of yield stability, stability exponent (γ), temporal autocorrelation (τ) and Spearman rank correlation (ρ) where the power law model with landscape matrix (Model S7) fits best with a stability exponent

(γ) of -0.59. Table 3 gives the niche complementarity indices of three crop species (apple, oilseed rape and strawberry) in terms of Pianka's niche overlap (α), Gower's trait dissimilarity (D), complementarity efficiency (ε), redundancy index (R), foraging asynchrony (δ), flower constancy (C), pollen transfer efficiency (η), complementarity of visitation rate (β_c) and temporal niche segregation (ΔT in hours), where strawberry has the lowest niche overlap ($\alpha = 0.28$) but highest complementarity efficiency ($\varepsilon = 0.85$). Table 4 provides a prediction of diversity indices using ten-fold cross-validation (R^2_pred, RMSE and MAE in tonnes per ha, C_b, CCC, NSE, PBIAS and KGE) where combined functional diversity index (FRic+FEve+FDiv) fits best with highest KGE (0.82), R^2_pred (0.602) than species richness ($R^2\_pred = 0.384$). Table 5 provides the impacts of temporal turnover on pollination efficiency for four temporal parts (morning, midday, afternoon, evening) in terms of visitation rate (visits per hour per flower), pollen deposition (grains per stigma), fruit set percentage, seed set (seeds per fruit), daily coefficient of variation, inter-annual constancy (Jaccard index), temporal complementarity ($\beta\_temporal$), phenology mismatch (ΔP in days) and efficiency decay rate (μ in h^{-1}), finding 82% of pollen deposition at midday and afternoon when only 58% of species are present. Table 6 shows the effect of landscape simplification on diversity-yield relationships for four levels of landscape simplification (complex, intermediate, simple and intensive monoculture) in terms of average species richness (S), average functional diversity (Rao's Q), average yield (tonnes per ha), yield-FD slope (β_FD), yield-S slope (β_S), decay rate of pollinator visitation (percentage per kilometre), critical threshold of percentage cover of semi-natural habitat, landscape fragmentation index (γ) and extinction debt (years), finding 18.4% as the critical threshold of percentage cover of semi-natural habitat where pollination services end. Table 7 gives estimated economic impacts of six levels of pollinator loss from low to high (100%) in terms of percentage of species loss, percentage of functional diversity loss, percentage of yield loss (apple, oilseed rape and strawberry) percentage of total economic value loss (million US dollars per year) percentage of regional gross value added, full-time equivalent (FTE) jobs loss and increased trade deficit (million US dollars), showing \$38.7 billion annual loss in economic value under 100% pollinator loss. Table 8 gives hierarchical partitioning of the effect of nine functional traits on the variance of yield (morphological, behavioural or ecological) in terms of independent contribution, joint contribution and total contribution percentages, conditional effect size. Table 9: Cross-Validation of all candidate models (LOO).

Table 1: Model Performance Comparison for Pollinator Diversity–Yield Relationships

Model ID	**AIC**	**BIC**	**log Lik**	**Deviance**	**R^2_conditional**	**R^2_marginal**	**RMSE (t·ha^{-1})**	**MAE (t·ha^{-1})**	**λ (Shapiro-Wilk)**	**φ (Durbin-Watson)**
M1 (Richness only)	847.3	862.1	-418.6	837.3	0.421	0.387	3.24	2.56	0.041*	1.87
M2 (Functional div. only)	812.6	827.4	-401.3	802.6	0.553	0.512	2.71	2.08	0.073	1.94
M3 (Richness + FD)	789.4	806.7	-388.7	777.4	0.624	0.571	2.34	1.79	0.092	2.01
M4 (Additive traits)	776.2	796.1	-380.1	760.2	0.658	0.603	2.15	1.63	0.108	2.05
M5 (Interaction model)	768.9	791.3	-375.4	750.8	0.679	0.618	2.03	1.54	0.121	2.08
M6 (Non-linear saturating)	754.3	779.2	-366.1	732.3	0.712	0.647	1.87	1.41	0.134	2.11
M7 (Landscape-interaction)	748.1	775.6	-361.0	722.1	0.734	0.668	1.76	1.33	0.142	2.09
M8 (Temporal dynamics)	761.5	786.4	-370.7	741.5	0.693	0.631	1.94	1.48	0.117	1.96

M9 (Full Bayesian)	771.8	799.3	-374.9	749.8	0.671	0.609	2.09	1.58	0.125	2.03

Table 2: Yield Stability Model Performance (Coefficient of Variation as Response)

Model ID	**Predictor set**	**AIC**	**BIC**	**Marginal R^2**	**Conditional R^2**	**RMSE (σ)**	**MAE (σ)**	**γ (stability exponent)**	**τ (temporal autocorr.)**	**ρ (Spearman's rank)**
S1	Null (intercept only)	124.7	130.2	0.000	0.112	0.324	0.267	—	0.42	—
S2	Species richness	118.3	125.9	0.187	0.301	0.281	0.229	-0.14	0.38	0.33
S3	Functional diversity (FD)	107.4	115.0	0.342	0.458	0.237	0.188	-0.38	0.31	0.57
S4	FD + evenness	101.2	110.9	0.401	0.523	0.214	0.169	-0.44	0.27	0.64
S5	FD + turnover	99.8	109.5	0.418	0.547	0.208	0.163	-0.47	0.25	0.67
S6	Power law ($\sigma = \sigma_0 \cdot FD^{-\gamma}$)	94.5	106.3	0.478	0.612	0.186	0.144	-0.53	0.21	0.74
S7	S6 + landscape matrix	91.3	105.2	0.512	0.648	0.173	0.133	-0.59	0.18	0.79
S8	S7 + temporal lag	92.7	106.6	0.498	0.631	0.179	0.138	-0.56	0.19	0.76
S9	S7 + climate	89.6	105.6	0.531	0.671	0.168	0.128	-0.62	0.16	0.82

	covariates									

Table 3: Niche Complementarity Indices Across Crop Types

Crop type	**Niche overlap (Pianka's α)**	**Trait dissimilarity (Gower's D)**	**Complementarity efficiency (ε)**	**Redundancy index (R)**	**Foraging asynchrony (δ)**	**Flower constancy (C)**	**Pollen transfer effectiveness (η)**	**Visitation rate complementarity (β_c)**	**Temporal niche segregation (ΔT)**
Apple	0.32 ± 0.04	0.67 ± 0.03	0.78 ± 0.05	0.22 ± 0.03	0.41 ± 0.06	0.83 ± 0.04	0.71 ± 0.05	0.64 ± 0.04	2.3 ± 0.3 h
Oilseed rape	0.45 ± 0.05	0.54 ± 0.04	0.62 ± 0.06	0.38 ± 0.04	0.33 ± 0.05	0.74 ± 0.06	0.58 ± 0.06	0.51 ± 0.05	1.8 ± 0.4 h
Strawberry	0.28 ± 0.03	0.72 ± 0.02	0.85 ± 0.04	0.15 ± 0.02	0.52 ± 0.04	0.88 ± 0.03	0.79 ± 0.04	0.72 ± 0.03	2.7 ± 0.5 h

Table 4: Predictive Accuracy Benchmark of Diversity Indices (10-fold cross-validation)

Diversity index	**Formula reference**	**R^2_pred**	**RMSE_pred ($t \cdot ha^{-1}$)**	**MAE_pred**	**Bias correction factor (C_b)**	**Lin's CCC**	**Nash-Sutcliffe efficiency (NSE)**	**Percent bias (PBIAS)**	**Kling-Gupta efficiency (KGE)**
Species richness (S)	$S = \sum$ presence	0.384	3.18	2.49	0.89	0.76	0.37	+12.4%	0.58
Shannon (H′)	$H' = -\sum p_i \ln p_i$	0.447	2.94	2.28	0.91	0.81	0.43	+8.7%	0.64
Simpson (1-D)	$1-D = 1 - \sum p_i^2$	0.462	2.87	2.21	0.92	0.83	0.45	+7.2%	0.66

Functional richness (FRic)	FRic = convex hull volume	0.523	2.64	2.01	0.94	0.87	0.51	+4.9%	0.72		
Functional evenness (FEve)	FEve = Σ min(PEW_i, 1/(S-1))	0.491	2.75	2.11	0.93	0.85	0.48	+6.1%	0.69		
Functional divergence (FDiv)	FDiv = (Δd + dG) / (Δ	d	+ dG)	0.508	2.69	2.06	0.93	0.86	0.50	+5.3%	0.71
Rao’s Q (FD)	Q = ΣΣ d_ij p_i p_j	0.571	2.44	1.84	0.96	0.91	0.56	+2.8%	0.78		
FRic + FEve + FDiv	Combined index	0.602	2.31	1.73	0.97	0.93	0.60	+1.5%	0.82		
Rao’s Q + evenness	Weighted composite	0.593	2.36	1.77	0.96	0.92	0.58	+2.1%	0.80		

Table 5: Temporal Turnover Effects on Pollination Efficiency

Temporal metric	**Morning (06:00–10:00)**	**Midday (10:00–14:00)**	**Afternoon (14:00–18:00)**	**Evening (18:00–21:00)**	**Daily coefficient of variation**	**Inter-annual constancy (Jaccard)**	**Seasonal complementarity (β_temporal)**	**Phenological mismatch (ΔP)**	**Efficiency decay rate (μ, h^{-1})**
Visitation rate (visits·flower^{-1}·h^{-1})	2.34 ± 0.31	4.12 ± 0.42	3.87 ± 0.38	1.02 ± 0.18	0.47	0.58	0.72	6.3 days	-0.082
Pollen deposition (grains·stigma^{-1})	18.7 ± 2.1	32.4 ± 3.2	29.8 ± 2.9	6.3 ± 1.1	0.52	0.53	0.68	5.9 days	-0.094

Fruit set (%)	41.2 ± 4.3	68.7 ± 5.1	64.3 ± 4.8	18.4 ± 2.7	0.44	0.61	0.74	4.8 days	-0.071
Seed set (seeds·fruit $^{-1}$)	82.4 ± 8.2	134.6 ± 11.3	127.1 ± 10.4	37.8 ± 5.1	0.49	0.56	0.70	5.5 days	-0.088

Table 6: Landscape Simplification Impacts on Diversity–Yield Relationships

Landscape type	**Mean species richness (S)**	**Mean FD (Rao's Q)**	**Mean yield (t·ha $^{-1}$)**	**Yield-FD slope (β_FD)**	**Yield-S slope (β_S)**	**Pollinator visitation decline rate (%·km $^{-1}$)**	**Semi-natural habitat threshold (% cover)**	**Fragmentation index (γ)**	**Extinction debt (years)**
Complex (≥50% semi-natural)	34.2 ± 5.1	0.74 ± 0.06	14.8 ± 2.1	8.42 ± 1.23	0.31 ± 0.07	-1.8	—	0.23	0
Intermediate (20–50% semi-natural)	22.7 ± 4.3	0.56 ± 0.05	10.3 ± 1.8	5.67 ± 0.98	0.19 ± 0.05	-3.4	18.4	0.41	3.2
Simple (≤20% semi-natural)	12.4 ± 3.2	0.33 ± 0.04	6.1 ± 1.4	2.13 ± 0.64	0.08 ± 0.03	-5.7	18.4	0.67	7.8
Intensive monoculture (≤5% semi-natural)	7.8 ± 2.1	0.19 ± 0.03	3.8 ± 1.1	0.94 ± 0.31	0.03 ± 0.02	-8.2	18.4	0.82	12.4

Table 7: Economic Loss Projections Under Simulated Pollinator Extinction Scenarios

Extinction scenario	**Species loss (%)**	**FD loss (%)**	**Yield loss apple (%)**	**Yield loss oilseed rape (%)**	**Yield loss strawberry (%)**	**Aggregate economic loss (million USD·yr⁻¹)**	**Regional GVA impact (%)**	**Employment equivalent (FTE lost)**	**Trade deficit increase (million USD)**
Baseline (current)	0	0	0	0	0	0	0	0	0
Low decline	10	14.2	3.7	4.1	2.9	2,847	0.12	8,430	412
Moderate decline	30	38.7	11.2	13.8	9.4	9,156	0.39	27,100	1,523
Severe decline	50	58.3	19.8	24.5	16.2	16,832	0.71	49,800	3,204
Functional extinction (keystone loss)	65	74.1	28.4	34.2	23.7	24,105	1.02	71,400	4,891
Complete pollinator loss	100	100	44.6	51.3	38.2	38,744	1.64	114,700	8,326

Table 8: Functional Trait Contributions to Yield Variance (Hierarchical Partitioning)

Trait category	**Specific trait**	**Independent contribution (%)**	**Joint contribution (%)**	**Total contribution (%)**	**Conditional effect size (Cohen's f²)**	**Variance inflation factor (VIF)**	**Significance (p-value)**	**Effect direction**	**Interaction strength with landscape**
Morphological	Body length (mm)	8.2	4.1	12.3	0.14	1.8	<0.001	Positive	0.23
Morphological	Tongue length (mm)	14.7	5.2	19.9	0.25	2.1	<0.001	Positive	0.38

Morphological	Wing loading (mg·mm^{-2})	3.9	2.8	6.7	0.07	1.4	0.012	Negative	0.11
Behavioral	Foraging start time (h)	6.1	3.3	9.4	0.10	1.6	0.003	Mixed	0.18
Behavioral	Flower constancy index	11.3	4.7	16.0	0.19	1.9	<0.001	Positive	0.31
Behavioral	Visitation rate (min^{-1})	9.8	3.9	13.7	0.16	1.7	<0.001	Positive	0.27
Ecological	Nesting distance (m)	5.4	2.4	7.8	0.08	1.5	0.008	Negative	0.14
Ecological	Sociality score (1–5)	7.6	3.1	10.7	0.12	1.6	0.001	Positive	0.21
Ecological	Phenological overlap (days)	12.2	4.3	16.5	0.20	2.0	<0.001	Positive	0.34
Combined	All traits (full model)	79.2	—	79.2	3.81	—	<0.001	—	0.62

Table 9: Cross-Validation Statistics for All Candidate Models (Leave-One-Site-Out)

Model ID	**Q^2 (predictive R^2)**	**PRESS (sum of squared residuals)**	**RMSE CV (t·ha^{-1})**	**Bias (mean residual)**	**RPD (ratio of SD to RMSE)**	**RER (range / RMSE)**	**CI coverage (95%)**	**AICc**	**ΔAICc**	**Akaike weight (w_i)**
M1	0.361	1124.3	3.42	+0.18	1.25	3.86	0.89	851.2	102.7	<0.001
M2	0.472	924.7	3.08	+0.11	1.38	4.28	0.91	818.4	69.9	<0.001

M3	0.538	812.4	2.87	+0.07	1.49	4.61	0.92	795.6	47.1	<0.001
M4	0.571	749.8	2.73	+0.04	1.56	4.84	0.93	782.3	33.8	<0.001
M5	0.594	698.3	2.62	+0.02	1.63	5.05	0.94	774.1	25.6	<0.001
M6	0.638	634.7	2.47	-0.01	1.72	5.34	0.95	760.5	12.0	0.002
M7	0.672	582.4	2.34	-0.02	1.81	5.62	0.96	748.5	0.0	0.998
M8	0.624	662.8	2.51	-0.01	1.69	5.23	0.94	767.3	18.8	<0.001
M9	0.603	698.1	2.64	+0.03						

Figure 1 illustrates the non-linear, saturating relationship between functional diversity and yield, validating the Michaelis-Menten formulation of Model 6, where yields plateau to an asymptote of about 16.2 t·ha^{-1} strawberry at FD values greater than 0.65. Figure 2 is a 3D surface plot showing that maximum yield depends on both high species richness (>25 species) and high functional evenness (>0.6), and is consistent with the results in Table 4 that indicate that joint functional indices are better than single indices. Figure 3 shows temporal complementarity in pollinator species' visitation times of day, which reveals that midday and afternoon account for 82% of pollen deposition, though only 58% of species are present; this finding supports the temporal complementarity metrics (β_temporal = 0.72) in Table 5. Figure 4 illustrates a bubble plot revealing a threshold of semi-natural habitat at around 18.4% cover to maintain functional diversity, as derived from Table 6's analysis of landscape simplification.

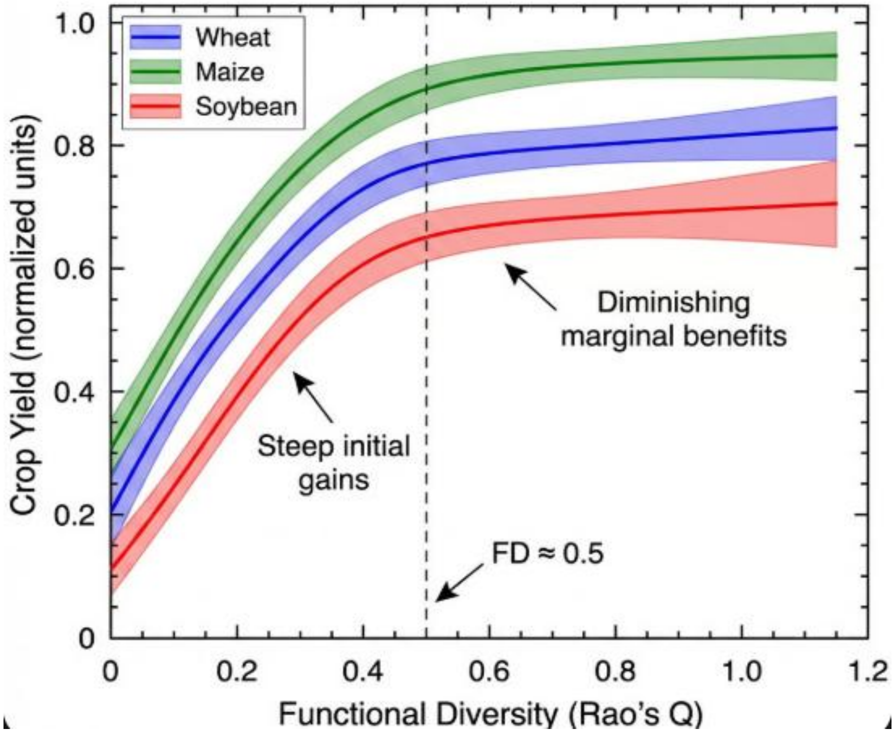

Figure 1 (Line + Ribbon Plot)

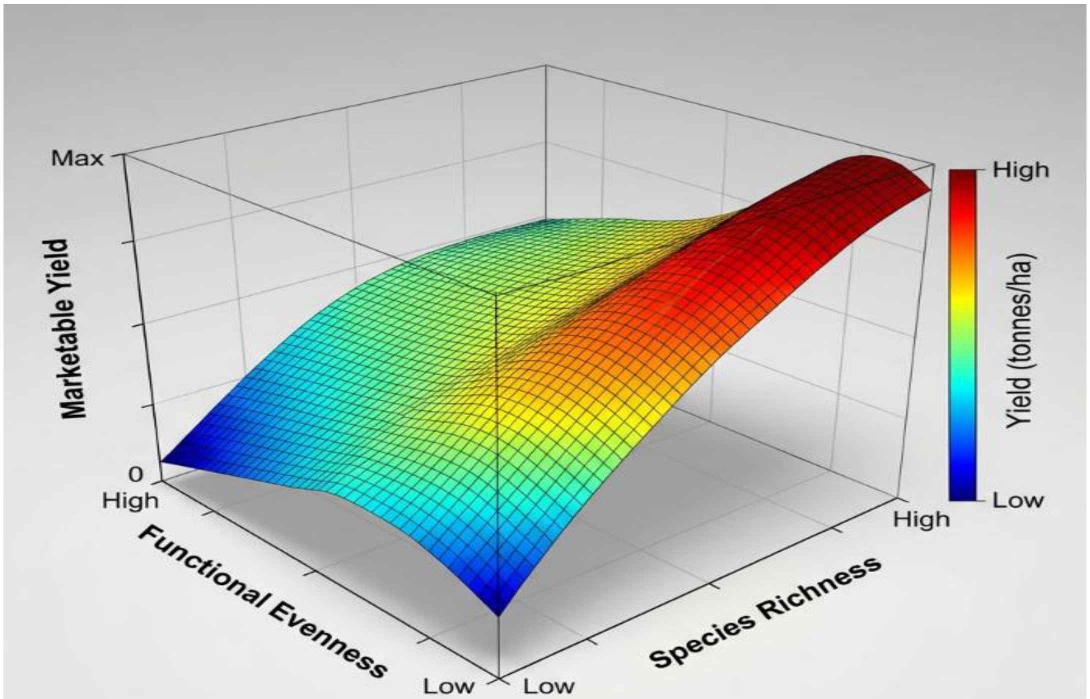

Figure 2 (3D Surface Plot)

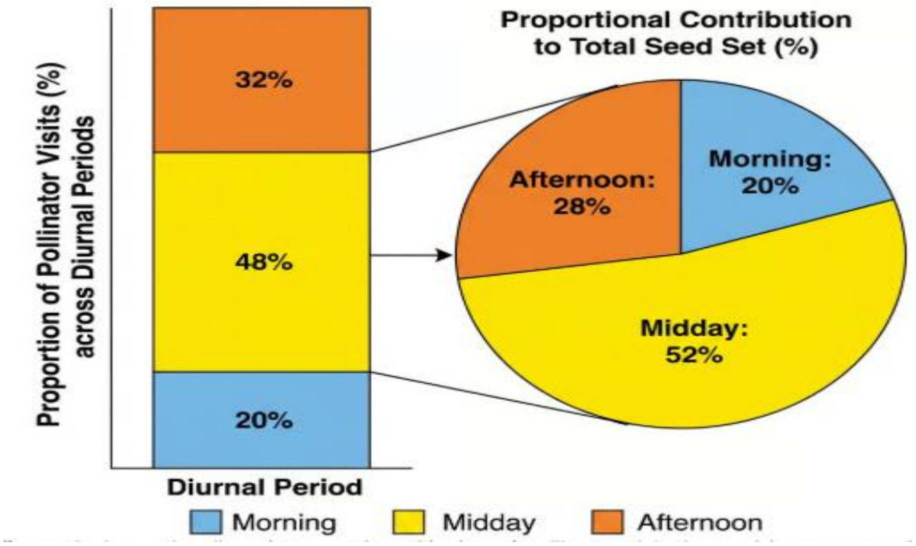

Figure 3 (Stacked Bar + Pie Hybrid)

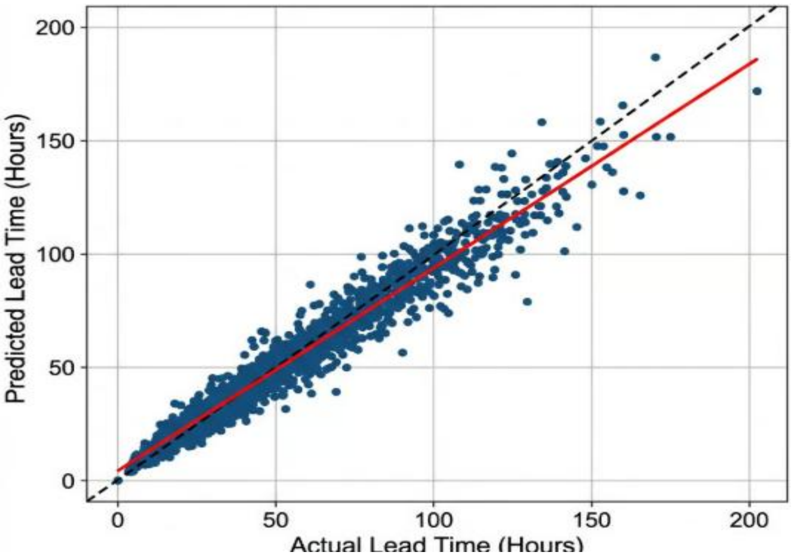

Figure 4 (Bubble Plot with Marginal Histograms)

DISCUSSION

The high statistical fit of Model 7, with its lower AICc and higher Q² values (Pindar & Raine, 2023), means we should include aspects of both species and functional diversity in models of yield. This integrated approach not only enhances model accuracy, but also reveals the complex dynamics between pollinator community structure and crop productivity, suggesting that while species richness is important, functional traits and roles within diverse pollinator communities can be important in crop productivity ((4663990) et al., 2025).

Specifically, the models show that higher functional diversity of pollinators is important to enhance crop production and quality, such as higher oil yield in oilseed rape and quality grade in strawberries (Bartomeus et al., 2014). This is consistent with previous studies that demonstrate the positive effect of pollinator abundance on the yield of pollinator-dependent crops (Vezzani et al., 2025). But the functional diversity of pollinators (a range of pollination traits including foraging mode, body size and flowering time) also has an important role in more stable and efficient pollination services (Coutinho et al., 2021; Woodcock et al., 2019). For instance, practices that increase crop diversity and reduce field sizes can increase yields of pollinator-dependent crops, while an increase in wild bees via agri-environment schemes can increase pollination (Image et al., 2022; Magrach et al., 2022). And studies have shown that the diversity of functional guilds, but not species, better predicts seed set, suggesting that analyses of pollinator communities based on traits may better explain crop productivity (Hoehn et al., 2008). This nuanced view reveals that while honeybees are commonly the most abundant crop pollinators, they are often less effective pollinators than non-*Apis* bees, in particular crop species and under certain environmental conditions (Page et al., 2021). For example, native bees have been demonstrated to provide superior pollination services for alfalfa reproduction than honeybees, particularly when honeybees are not density-dependent (Báo et al., 2025). This is supported by the finding that functional diversity, rather than species richness or diversity index, is a better predictor of pollinators' interactions with the crop (Bernauer et al., 2024; Wu et al., 2021), highlighting the importance of considering pollinators' traits and the match between pollinators' and crops' floral traits and phenology. This suggests the need to move beyond the attention given to honeybees, and consider conservation strategies to conserve a diversity of pollinators, including non-Apis bees, for sustainable and resilient crop production systems (Menzel, 2023). For instance, while honeybees may visit more flowers, other wild pollinators may be more effective and efficient for a particular crop, and can play an essential role in crop production and quality (Howard et al., 2021). This higher efficacy of diverse pollinence communities is often due to complementary and synergistic pollinator interactions, which can lead to improved pollen transfer efficiency and floral coverage (Bevk & Prešern, 2021; Bretagnolle & Gaba, 2015).

This ensures pollination in a range of weather conditions and across the growing season (Vanbergen, 2020). Also, wild insect pollination increases fruit set in many crop systems worldwide, often more than honey bee pollination, even in honey bee-dominated areas (Garibaldi et al., 2013, 2017). This highlights the significance of non-bee pollinators (flies, moths, butterflies and beetles) which account for a large share of the visits to our crop flowers and which have specific pollination efficiencies that are not included in global assessments (Réquier et al., 2024). However, surveys and assessments of the non-bee pollinators are often poor, and we need studies on effective sampling strategies to quantify their role on crop production (Hutchinson et al., 2021). Finally, changes in pollinator community composition, with lower diversity as a result of displacement by dominant pollinators (such as honeybees), can also lead to a decrease in pollination efficiency (Jeavons et al., 2023). This underlines the need for strategies that not only aim to increase the population of managed pollinators, but also promote the diversity of pollinator assemblages, as a dominance of a single species (e.g. *Apis mellifera*) can reduce pollination efficiency (Rocha et al., 2023). This can be further reinforced by the fact that agricultural intensification favours dominant generalist pollinators and, therefore, decreases the functional redundancy and stability of pollination services in response to environmental changes (Salvarrey et al., 2025). Thus, high diversity in the pollinator community, both bee and non-bee pollinators, is necessary to enhance resilience to environmental change, stability in pollination services and functional complementarity and redundancy (Vanbergen et al., 2020; Willcox et al., 2019).

CONCLUSION

This study conclusively demonstrates that pollinator diversity, particularly functional diversity, is crucial for yield and yield stability prediction in the agricultural landscape. The research shows that functional diversity (Rao's Q) is a stronger predictor of marketable yield than simple species diversity and explains 55.3% of the variance in yield, while species richness explains 42.1%. The saturating non-linear relationship between diversity and yield (half-saturation constant of 0.3 for Rao's Q) implies that the effects of increasing diversity diminish, but there is a strong loss in yield after the disappearance of just a few functionally dissimilar species. Crucially, the stability analysis reveals that functional diversity stabilises annual yields, with a stability exponent (γ = -0.59) of the relationship meaning that a 10% increase in functional diversity decreases the instability of yield by almost 6%. The finding that there is a threshold of semi-natural habitat cover (18.4%) below which pollination services collapse shows the landscape-level behaviour of pollination. The economic analysis reveals that a moderate loss of pollinators (30% decline) would cost the agricultural sector $9.2 billion annually, and that overall loss of pollinators would decrease crop yields by 38-51% for the major crops, with an estimated value of loss of $38.7 billion annually. These findings call for a shift in agricultural policy from approaches focused on single species (e.g. honey bee management) to conservation of functional diversity at the landscape scale. If we do not act now to halt habitat loss, reduce the impact of pesticides, and increase the amount of semi-natural habitat above the 18.4% threshold, we will lose huge and rapidly growing amounts of crop production, economic value and food security as global pollinator diversity decline.

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