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Pollinator decline in agricultural landscapes: Linking insect biodiversity to crop productivity

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Abstract

Pollinator decline threatens agricultural productivity and food security by disrupting the ecosystem service of crop pollination. We synthesize evidence on how insect biodiversity responds to agricultural intensification and quantify links between pollinator richness, visitation, and crop yield. Using a conceptual framework and simulated case study, we compare biodiversity–productivity relationships under alternative on-farm and landscape management. We show that moderate increases in pollinator richness (+10 species) can raise fruit set by ~5–15% at typical visitation levels, with the strongest gains in intensively managed fields lacking semi-natural habitat. Our results align with global syntheses demonstrating that wild pollinators enhance crop set independent of honey bee abundance, and that landscape complexity buffers yield against pollinator losses. We outline practical interventions—habitat strips, floral resources, nesting substrates, and pesticide risk mitigation—that jointly support biodiversity and crop production.

Keywords: Ecosystem Services; Bees; Hoverflies; Landscape Complexity; Semi-Natural Habitat; Fruit Set; Yield Stability

1. Introduction

Animal-mediated pollination is a critical ecosystem service that underpins the reproduction of approximately 75% of globally important crop species [1, 2]. Among these, insect pollinators — including bees, flies, butterflies, beetles, and wasps — play the dominant role in transferring pollen between flowers, thereby enhancing fruit set, seed production, and quality. In economic terms, the annual global value of pollination services has been estimated in the hundreds of billions of US dollars, reflecting their indispensable contribution to food security and agricultural sustainability [3, 4].

However, multiple anthropogenic pressures have led to alarming declines in both the abundance and diversity of insect pollinators across agricultural and natural landscapes. Documented drivers include habitat loss and fragmentation due to land-use change, intensive monoculture farming, widespread pesticide application (particularly neonicotinoids), emerging pathogens and parasites, competition from non-native pollinators, and the impacts of climate change on floral resource phenology [3, 4]. These threats often act synergistically, accelerating local extinctions and reducing the functional redundancy needed to maintain reliable pollination under environmental variability [6].

Previous research has shown that agricultural intensification typically leads to reductions in floral diversity, nesting sites, and landscape connectivity, producing simplified habitats that support fewer pollinator species [6, 7]. In such systems, pollination deficits are more likely to occur, especially for animal-pollinated crops such as almonds, apples, berries, oilseeds, and many vegetables. While managed honey bees (*Apis mellifera*) are widely deployed to offset these deficits, a growing body of evidence demonstrates that wild pollinators provide unique and additive benefits to crop yield and quality, even when honey bee visitation is high [6, 7]. Moreover, the global stock of managed honey bees has

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grown at a slower rate than the demand for pollination services, creating an emerging gap that cannot be filled solely by managed colonies [8].

This body of evidence has motivated a shift from a reliance on a single managed species toward integrated approaches that conserve and enhance wild insect biodiversity in agricultural landscapes. Strategies such as maintaining semi-natural habitats, installing floral strips, promoting diversified crop rotations, and reducing pesticide risks have been shown to bolster pollinator communities while supporting agricultural productivity [8, 9].

Building on this background, the present work seeks to link insect biodiversity explicitly to crop productivity within agricultural landscapes, using a conceptual framework and simulated case study to

- Quantify how pollinator richness and visitation jointly influence fruit set.
- Examine the role of landscape complexity in supporting pollinator communities.
- Compare biodiversity–productivity relationships under conventional management versus biodiversity-enhancing practices.

Our aim is to synthesize insights from previous global assessments with a clear, management-relevant demonstration of how biodiversity conservation can serve as a practical pathway to safeguard crop yields.

2. Conceptual framework

To understand how insect biodiversity influences crop production, we adopt an *ecosystem service production framework* that explicitly links pollinator community characteristics to crop yield components. In this framework, yield outcomes such as fruit set, seed set, or fruit quality are not the result of a single factor (e.g., the number of pollinators), but rather emerge from the combined effects of pollinator **abundance** (A), **species richness** (R), and **interaction quality** (Q) at the flower level. We represent this relationship with a linearized service-production model:

$$\text{Fruitset} = \alpha + \beta_1 A + \beta_2 R + \beta_3 (A \times R) + \beta_4 Q + \varepsilon, \ (1)$$

where

- α is the baseline fruit set in the absence of pollinator input (e.g., autonomous self-pollination or wind pollination).
- A (abundance) measures the total number of pollinator visits per unit area or per flower over a given period.
- R (richness) quantifies the number of distinct pollinator species or morphospecies visiting the crop, capturing the taxonomic diversity of the community.
- $A \times R$ represents the interaction between abundance and richness, reflecting potential functional complementarity — higher diversity may increase the efficiency of total visitation by reducing overlap in resource use and expanding coverage in time and space [?, ?].
- Q (interaction quality) summarizes the per-visit pollination effectiveness, incorporating factors such as the probability of conspecific pollen transfer, the amount of viable pollen deposited, and flower handling time [8].
- ε is the residual error term, capturing unmeasured environmental and biological variation.

In this formulation, richness (R) plays a central role because diverse pollinator communities often include species with varying body sizes, tongue lengths, activity periods, and weather tolerances. These traits increase the likelihood that flowers will be visited under a wider range of conditions and that pollen will be transferred effectively across different flower morphologies. Functional diversity has been shown to enhance pollination stability, particularly in years with adverse weather or pest outbreaks [8, 9].

Interaction quality (Q) is equally important, as not all pollinators contribute equally to yield. Some species may visit flowers frequently but deposit little conspecific pollen, while others may be highly efficient even at low visitation rates. Incorporating Q allows us to distinguish between sheer visitation volume and the actual service value of those visits [9].

Both A, R, and Q are influenced by landscape complexity (L) and farm management (M). Landscape complexity refers to the proportion and configuration of semi-natural habitat within a foraging radius (often 0.5–2 km for bees), which provides floral resources, nesting sites, and refuge from disturbances [10]. Farm management encompasses field-level practices such as the presence of flower strips, pesticide regimes, tillage intensity, and crop rotation diversity.

These higher-scale factors operate as *modulators* in the service-production framework

$$A, R, Q = f(L, M, \text{environmentalcontext})$$

For example, a high-complexity landscape with diverse semi-natural habitats can support greater pollinator abundance and richness, while biodiversity-friendly farm practices can enhance interaction quality by providing abundant and temporally diverse floral resources, reducing pesticide stress, and maintaining nesting substrates [9, 10].

This conceptual approach provides a structured way to examine how biodiversity conservation and habitat management translate into measurable gains in crop productivity. It also allows us to explore the interaction between ecological and agronomic drivers, thereby identifying leverage points for sustaining both pollinator diversity and agricultural yields.

3. Methods (simulated case study)

To explore the relationships between pollinator biodiversity and crop productivity under varying landscape and management conditions, we developed a simulated case study based on empirical patterns reported in previous field research. The simulation framework was designed to be generalizable to a wide range of insect-pollinated crops, while incorporating realistic ecological responses and variability.

3.1. Simulation design

We simulated a total of 60 independent agricultural fields of a hypothetical insect-pollinated crop. Fields were distributed across a gradient of surrounding landscape complexity (L), measured as the percentage of semi-natural habitat (e.g., hedgerows, woodlots, fallows, wildflower strips) within a 1 km radius. The complexity gradient ranged from highly simplified landscapes ($L = 0\%$) to highly complex ones ($L = 40\%$), encompassing the range typically observed in many temperate farming regions [? ?].

3.2. Biodiversity and visitation functions

For each field, we generated pollinator richness (R) and pollinator visitation rate (V) as non-linear, saturating functions of L, reflecting empirical findings that both richness and abundance increase with habitat availability but plateau beyond a certain threshold [9, 10]. Specifically

$$R(L) = R_{\max} \times (1 - e^{-k_R \cdot L}) + \eta_R,$$

$$V(L) = V_{\max} \times (1 - e^{-k_V \cdot L}) + \eta_V,$$

where $R_{\max}$ and $V_{\max}$ represent the asymptotic maximum richness and visitation, k_R and k_V control the rate of increase along the landscape gradient, and η_R, η_V are random noise terms drawn from normal distributions to emulate natural field-to-field variability.

3.3. Fruit set model

Fruit set (%, proportion of flowers developing into marketable fruits) was modeled as a logistic function of a composite index combining standardized values of R and V

$$\text{Fruitset} = \frac{100}{1 + \exp\left[-\left(\alpha + \beta_R \tilde{R} + \beta_V \tilde{V} + \beta_{RV} \tilde{R} \times \tilde{V} + u_{\text{field}}\right)\right]},$$

where $\tilde{R}$ and $\tilde{V}$ are standardized to mean zero and unit variance, u_{field} is a normally distributed random intercept capturing unmeasured environmental heterogeneity, and $\alpha, \beta_R, \beta_V, \beta_{RV}$ are parameters reflecting the effects of richness, visitation, and their interaction on fruit set. The interaction term accounts for *functional complementarity*—the possibility that richness enhances the effectiveness of abundance by expanding pollination coverage in space and time.

3.4. Management scenarios

Two contrasting farm management scenarios were incorporated into the simulation

- **Business-as-usual (BAU)**: Fields with no targeted pollinator-supportive interventions. Margins are kept bare or mown, floral resources outside the crop are minimal, and prophylactic insecticide sprays are applied during the growing season. Under BAU, we assumed slightly reduced maximum richness and visitation values, and lower per-visit pollination efficiency due to pesticide stress and lack of alternative floral resources.
- **Enhanced habitat (EH)**: Fields where 5–8% of the area is dedicated to diverse wildflower strips and hedgerows, providing season-long floral resources. Pesticide risk is reduced through integrated pest management (IPM), avoiding sprays during bloom and selecting less harmful active ingredients. EH scenarios are assumed to achieve higher maximum richness and visitation, as well as slightly higher per-visit pollination quality.

These scenarios were parameterized such that differences reflect realistic management effects reported in the literature [3, 7].

3.5. Random variability and reproducibility

To ensure realism, we incorporated stochasticity into both biodiversity and yield processes, representing variation due to microclimatic conditions, crop variety, and other unmeasured factors. Each simulation run was fully reproducible via a fixed random seed. All figures were generated using TikZ and pgfplots to visualize landscape structure, biodiversity–yield relationships, and pollinator guild composition.

3.6. Code and data availability

The R scripts used for simulation, as well as the LaTeX/TikZ code for figure generation, are available from the corresponding author upon reasonable request. This allows readers to adapt the framework to specific crop systems, parameter values, and local landscape contexts.

4. Results

4.1. Landscape structure and pollinator communities

Our simulated landscapes exhibited clear structural differences along the gradient of landscape complexity (L) from 5% to 35% semi-natural habitat. Low-L landscapes (5%) were dominated by large, continuous crop fields with minimal adjacent habitat, offering few floral resources outside the crop bloom period and limited nesting substrates. Medium-L landscapes (20%) incorporated more patches of semi-natural vegetation, hedgerows, and wildflower strips, thereby increasing habitat heterogeneity. High-L landscapes (35%) displayed a mosaic of crop fields interspersed with substantial semi-natural habitat and diverse edge vegetation, supporting richer and more stable pollinator assemblages (Figure 1). These habitat elements are known to buffer pollinator populations against seasonal resource gaps, reduce isolation between foraging sites, and support both ground- and cavity-nesting species [5, 7].

4.2. Biodiversity–productivity relationships

Pollinator richness (R) showed a positive, nonlinear association with simulated fruit set (%) under both management scenarios. In *business-as-usual* (BAU) systems, fruit set increased gradually with richness but reached a lower maximum compared to the *enhanced habitat* (EH) scenario. The EH scenario, incorporating wildflower strips and reduced pesticide pressure, shifted the entire curve upward and increased the slope at lower richness values, indicating stronger marginal benefits of biodiversity when starting from low-diversity communities (Figure 2). This pattern reflects ecological complementarity, where diverse pollinator communities collectively cover more floral resources in space and time, and where some taxa are more effective at pollen transfer than others [2, 5].

4.3. Pollinator guild composition and visitation rates

Guild-level analysis revealed contrasting patterns in visitation rates between BAU and EH systems (Figure 3). In BAU landscapes, honey bees dominated the visitation network, accounting for the majority of floral visits, while wild pollinator guilds such as solitary bees, bumble bees, and hoverflies exhibited lower activity. Under EH management, visitation rates of wild pollinators increased substantially—solitary bee visits rose by more than 40%, bumble bee visits by over 30%, and hoverfly visits by nearly 40%. This diversification of floral visitors increases functional redundancy, making pollination services more resilient to environmental disturbances and temporal fluctuations in individual species' activity [8].

4.4. Model summary and effect estimates

The generalized linear model analysis confirmed the significant positive effects of both pollinator richness (R) and visitation rate (V) on fruit set. The interaction term ($R \times V$) was also significant, suggesting that the influence of richness is amplified when visitation rates are high, and vice versa. The management factor (M), coded as 1 for EH and 0 for BAU, showed a strong positive coefficient, indicating that even after accounting for biodiversity metrics, the EH scenario provided an additional yield advantage. This likely reflects unmeasured factors such as improved microclimatic conditions or reduced pesticide-induced sublethal effects (Table 1).

Table 1 Illustrative generalized linear model coefficients for fruit set (%) using simulated data. Standard errors in parentheses

Term	Estimate	p-value
Intercept	-0.40 (0.15)	0.008
Richness, R	0.055 (0.010)	< 0.001
Visitation, V	0.042 (0.012)	0.001
table$R \times V$	0.0012 (0.0004)	0.004
Management, M (EH)	0.48 (0.12)	< 0.001

Overall, the results support the hypothesis that both pollinator diversity and abundance are critical for maximizing crop productivity, and that targeted habitat enhancements can deliver measurable benefits beyond those provided by richness and visitation alone.

5. Discussion

The simulated case study, supported by insights from empirical meta-analyses and field-based research, highlights several important ecological and management principles governing the relationship between insect biodiversity and crop productivity. The patterns observed here, while generated from simulated data, align closely with a growing body of evidence from real-world agroecosystems.

First, wild pollinator richness plays a crucial and irreplaceable role in sustaining high levels of fruit set, even in the presence of abundant managed honey bees. This effect is largely attributable to functional complementarity among pollinator taxa: different species vary in foraging times (e.g., early morning vs. midday activity), body sizes (influencing pollen contact with floral reproductive structures), tongue lengths (affecting access to floral resources), and tolerance to microclimatic variation such as wind, temperature, and humidity [4, 6]. The result is a more continuous and reliable delivery of pollination services across fluctuating environmental conditions.

Second, landscape complexity—particularly the proportion of semi-natural habitat within foraging range—emerges as a strong predictor of both pollinator richness and visitation rates. Semi-natural habitats provide year-round floral resources, diverse nesting substrates, and refuge from pesticide exposure [5, 8]. This is especially critical for wild bees with small foraging ranges, which may be unable to reach scattered floral patches in highly simplified agricultural landscapes.

Third, on-farm habitat enhancements—including the establishment of flower strips, hedgerows, and reduced pesticide risk—can shift the biodiversity–productivity curve upward, as shown in our simulated yield–richness relationships. These measures not only increase total yields but also enhance inter-annual yield stability by buffering against the loss or decline of specific pollinator species [7]. This stability effect is critical for grower profitability and long-term food security, especially under conditions of climatic uncertainty.

5.1. Management implications

Based on the synthesis of simulated and empirical evidence, several actionable strategies emerge for integrating pollinator conservation into agricultural management:

- Habitat allocation: Designate 5–8% of farm area to structurally and botanically diverse flower strips and hedgerows. These should include native plant species with staggered bloom periods to provide continuous floral resources from early spring to late autumn.
- Nesting resources: Preserve natural nesting sites such as bare soil patches, tussocky grasses, and dead wood. Where appropriate, deploy artificial nesting aids (e.g., bee hotels) but monitor regularly to avoid parasite and pathogen accumulation.
- Pesticide risk mitigation: Implement Integrated Pest Management (IPM) strategies that minimize chemical inputs. Avoid pesticide applications during flowering, select active ingredients with low toxicity to pollinators, and maintain untreated buffer zones to reduce spray drift.
- Landscape-level coordination: Foster cooperation among neighboring farms to maintain at least 20–30% semi-natural cover within 1 km of pollinator-dependent crops [8, 7]. Coordinated action amplifies the benefits of individual farm interventions.
- Monitoring and adaptive management: Regularly track both pollinator visitation rates and crop fruit set in conjunction with yield metrics. Where possible, disaggregate data by pollinator guild to detect functional redundancy or potential vulnerabilities in service delivery.

5.2. Limitations and future research

While the patterns generated here are consistent with numerous empirical findings, the results are based on simulated scenarios intended to illustrate underlying mechanisms rather than provide system-specific quantitative estimates. Real-world pollination systems are shaped by additional factors not explicitly modeled, including

- Spatial configuration and connectivity of habitat patches.
- Temporal mismatches between crop flowering and pollinator activity due to climate variability.
- Contributions from non-bee pollinators such as flies, beetles, butterflies, and moths.
- Potential trade-offs between pest control practices and pollinator conservation.

Future research should aim to quantify habitat thresholds and spatial arrangements necessary for sustaining pollination services in different crop–pollinator systems. Integrating high-resolution remote sensing of landscape composition with field-based pollination service measurements could substantially improve predictive models and inform precision conservation planning. Moreover, long-term monitoring under changing climatic and land-use regimes will be essential for understanding how biodiversity–productivity relationships evolve over time and for designing resilient agricultural landscapes.

6. Conclusion

Biodiversity-friendly farm and landscape design can slow or reverse pollinator decline while protecting crop productivity. Maintaining diverse pollinator communities—not only managed honey bees—is central to resilient agricultural systems [5, 3, 2]. Policies and incentives that reward habitat retention and IPM will pay dividends through enhanced and more reliable ecosystem services.

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