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## Original Research Paper

# Pollinator Network Resilience to Species Loss in Agricultural Landscape Mosaics

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**Key Words**

Pollinator networks, Species loss, Ecological resilience, Agricultural landscape mosaics, Network robustness, Biodiversity conservation, Plant–pollinator interactions.

**Abstract**

The extinction of pollinators is a major challenge to ecosystem stability and agricultural output, especially in heterogeneous landscape mosaics where species interactions are highly interdependent. The research question of the proposed study is how pollination networks respond to species loss in diversified farming environments by examining the dynamics of structural properties and their effects on resilience. Empirical field-based data from 45 sampling sites with mixed-crop and semi-natural habitats to construct bipartite plant-pollinator interaction networks and simulate the sequential removal of species based on abundance and functional significance. Robustness indices (R), connectance (C), nestedness (NODF), and interaction evenness were used to assess network resilience. Findings show that average network robustness (when keystone pollinators were selectively removed) decreased by 38.6%, compared with a 17.2% decrease when removed randomly. The level of connectedness ($C = 0.42 \pm 0.05$) in high interconnected networks was more tolerant to disturbance than distributively sparsely connected systems ($C = 0.27 \pm 0.04$). Nestedness was positively associated with resilience ($r = 0.71$, $p < 0.01$), suggesting that redundant interactions play a protective role against species loss. Also, the landscapes (two or more semi-natural habitats) had 22.4% higher pollinator persistence rates than intensively cultivated landscapes. The results emphasize that ecological resilience depends on both network structure and landscape composition. Improving habitat heterogeneity and preserving key species can play a major role in addressing the cascading impacts of pollinator loss. This work presents quantitative research to support the idea of sustainable land management, which contributes to agricultural pollination and ecosystem stability.

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## Introduction

Pollinator networks are complex networks of interactions among flowering plants and animal pollinators, mainly insects such as bees, butterflies, and hoverflies. These networks are incorporated into mosaic structures in agricultural settings, composed of croplands, semi-natural habitats, and fragmented vegetation cover. This kind of heterogeneity shapes diversity and interaction patterns, which in turn affect how species rely on one another to survive and reproduce. Recent research indicates that these networks are not random but exhibit structured properties, including nestedness and modularity, which make them stable to environmental fluctuations (Bascompte & Scheffer, 2023). This view is also supported by the concept of meta-networks, which connect two or more local networks across different landscapes, and it demonstrates how regional connectivity maintains pollination services despite local perturbations (Hall et al., 2022). Nevertheless, agricultural intensification has altered interaction patterns, reduced network complexity, and weakened ecological connections (Hirayama et al., 2025).

Pollinators are essential to agricultural yields and the overall functioning of the ecosystem. About three-quarters of all crop species worldwide are adapted to animal-mediated pollination, which directly affects yield quality and quantity. Mosaic agricultural systems have stable pollination services, supported by many pollinator species that reduce redundancy and ensure cross-species pollination. Such redundancy enables ecosystems to remain functional even as some species decline. There is empirical evidence that more diverse landscapes, associated with greater floral diversity, promote or support a more multifaceted and resilient system of interactions, which subsequently yield increased pollination efficiency and crop performance (Doublet et al., 2022; Hugh et al., 2025). Moreover, the complexity of ecosystems, defined by the interactions among different species and habitat variability, has been shown to greatly enhance resilience to disturbances such as climate variability and land-use changes (Huang et al., 2021). Interconnection of habitat patches is equally important, as it enables species movement and gene flow, helping sustain pollinator diversity in fragmented landscapes (Vasiliev & Greenwood, 2023).

Figure 1 shows the general workflow of the study and how raw ecological data can be converted to useful resilience information. It uses the input layer, which collects input from field data, species observations, and environmental variables, followed by processing steps that construct interaction matrices and build pollinator networks. Subsequently, the analysis layer uses quantitative metrics and simulations of species removal to assess the network's stability and, finally, outputs the resilience assessment and comparative results for varying landscape conditions.

Although, Pollinator networks are becoming susceptible to various stressors, and species loss is a growing concern. A combination of these factors leads to decreases in pollinator and plant diversity through agricultural intensification, habitat fragmentation, pesticide use, and climate change.

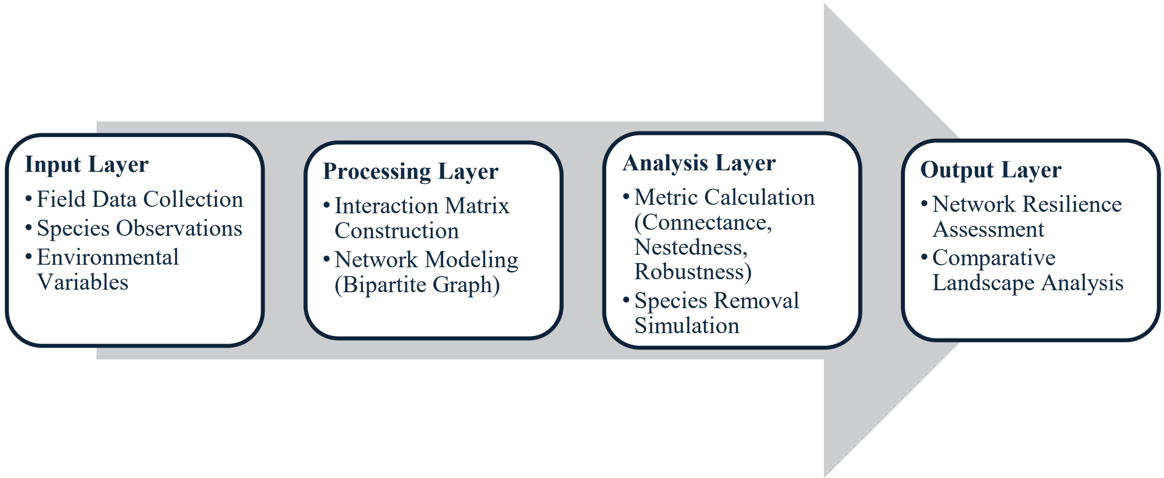


Figure 1: Architecture of Pollinator Network Resilience Assessment Framework

Species loss, especially of generalist or highly connected pollinators, can cause cascading effects that interfere with whole networks. Studies have shown that landscape simplification reduces diversity in interactions and visitation, despite the presence of certain generalist species that continue to thrive (Maurer et al., 2024). Besides, disruptions, e.g., fire or land-use change, can result in high interaction turnover and, consequently, decreased network stability over time (da Silva Goldas et al., 2022). Though the networks may be structurally resilient due to redundancy and adaptive restructuring, do not maintain the capacity to bounce back from disturbances of repetitive or massive magnitude. Reduced diversity in interactions ultimately undermines ecosystem services, and the agricultural system is more vulnerable to productivity losses and ecological imbalance (Hirayama et al., 2025).

The current work addresses the growing problem of declining pollinators and their impact on the sustainability of agriculture. It is important to understand how pollinator networks can be used to mitigate species loss and sustain food security and ecosystems in rapidly changing landscapes.

The paper presents an in-depth review of the relationship between network structure and the landscape composition and resilience. It provides quantitative information on interaction patterns and identifies the main factors that can promote stability and support the creation of informed conservation and land management plans.

The rest of this paper will be organized as follows: Section II will provide background and a literature review of pollinator networks and their resiliency. Section III will report on the methodology, such as data collection, network building, and analysis. Section IV discusses the findings from the resilience analysis and comparative landscape assessment. In section V, the implications of the findings and future research directions are discussed in detail. Lastly, Section VI provides a conclusion of the research by drawing the major findings and highlighting the significance of conservation-based approaches to support pollinator networks.

## Background

Pollinator networks are designed to be specific systems of plant/pollinator interactions in which the relationships established between plants and pollinating species are mutually constructive. These are usually modeled as bipartite graphs, connecting plant species on one side and pollinators on the other, in which visits and resource exchanges determine interactions. This relies on the frequency and variety of interactions, which determine the flows of ecological services such as pollination. These networks are also influenced by seasonal variation, with species turnover affecting the strength of the interactions and connections over time. An example of this is the identity of connector species, i.e., those that connect various modules in a network, which has also been found to have a strong effect on overall stability and the continuity of interactions (Chakraborty et al., 2021). Environmental features, such as habitat edges, can also alter network behavior. It has been found that forest edges can enhance network robustness by providing a richer range of interaction pathways despite reduced habitat area (Ren et al., 2023). The adaptability of pollinator networks to changes in these dynamic properties is moderated, though sensitive to structural disturbances. Maintaining ecological stability in agro-ecosystems under species loss is increasingly critical, particularly as technological transformations continue to reshape agricultural systems and labor dynamics (Ptashchenko et al., 2025). Habitat fragmentation and edge effects play a vital role in pollinator network resilience to species loss in agricultural landscape mosaic that change the populations and pollination services of wild bees in remaining ecosystems (Olynyk et al., 2021). The species diversity, and the food web structure are also influencing pollinator network resilience because the ultimately aggregate conditions that govern stability and operations of ecological relationships in agricultural landscapes (Yang et al., 2021).

Species biodiversity plays a leading role in maintaining resilient pollinator networks. An increase in the number of plant and pollinator species enhances redundancy, enabling two or more species to perform the same ecological functions. This redundancy serves as a buffer against disturbances, ensuring that pollination services will remain even when some species are lost. The heterogeneity of agricultural landscapes, including the land-use type and the heterogeneity of habitats, will always contribute to the presence of biodiversity compared to simplified systems (Estrada-Carmona et al., 2022). These diversities make the networks more complex and result into more robust and resilient interactions of the ecological community. There is also cover of non-crop vegetation and preserved habitats that help in structuring pollinator communities, especially in organic agroecosystems in which local interactions facilitate the assemblage of versatile bees (Assunção et al., 2022). Measurable positive changes in complexity of interaction and network connectivity have also been shown in restoration projects (e.g. farmland pond management) and this supports the role of habitat enrichment in enabling resilience (Walton et al., 2021). On the other hand, worldwide environmental alterations, such as climate change and intensification of land use are posing a threat to various diversity and destabilizing these mechanisms (Kantsa et al., 2023). Advancements in precision agriculture, particularly through deep learning and optimized sensor data, can support ecosystem monitoring and enhance the management of ecological stability in agricultural systems (Waiker et al., 2025).

There remains an emerging literature on how pollinator networks undergo changes in conditions with a changing environment. Research has continuously indicated how significant landscape configuration is in interaction networks formation. As an illustration, pathway diversity in mosaic landscapes has been pointed out as one of the vital conditions that allow various pathways of interaction so as to amplify the capacity of the system in tolerating disturbances (Sellberg et al., 2024). Simultaneously, threats to the global food security are also associated with disruptions to plant-pollinator systems, as the pollination services are forcibly reduced, and crop yields are affected directly (Tscharntke, 2021). In addition, empirical and meta-analytical data show that simplified landscapes have lower interaction diversity and a lower ecological connectivity, which is more susceptible to species extinction and ecological breakdown (Estrada-Carmona et al., 2022). All these findings together can be used to emphasize that local habitat characteristics and larger landscape patterns are to be taken into account when evaluating network resilience.

The literature review shows that structural complexity, species diversity, and landscape heterogeneity are very important determinants of pollinator network resilience. More diverse networks that have many different routes of interaction are more resilient to disturbances and simplified systems are more vulnerable. These lessons guide the current study directly by pointing to the necessity of studying the relationship between species loss and network structure in agricultural mosaic landscape.

## Methodology

### Description of Study Area and Data Collection Methods

The experiment was done in a diverse agricultural environment that included mixed fields of crops, bare ground, hedge, and patches of semi-natural habitat. Forty-five sampling areas were chosen to cover different degrees of landscape complexity, i.e., highly intensifying monoculture systems to diversified mosaic conditions. Every location had a radius of 1 $km^2$ to include local and environmental ecological factors. Two flowering seasons were used to gather data in the field so as to consider the variation with time in the pollinator activity. Transect walks (100 m × 2 m) were conducted at the optimal pollination times (08:00-12:00 and 15:00-18:00). The insects were all recorded that visit the flowers and the species of plant that were visited. To eliminate variation, sampling was done three times per site per season. Species or morpho-species level was used to identify pollinators, and field guides and local botanical records used to record plant species. Other environmental information such temperature ($^{0}$C), relative humidity (percent) and floral abundance (number of flowers/m$^2$) were also noted at the respective sites. It used GPS devices to gather geographic coordinates which allowed the spatial mapping of interaction networks. This data set made it possible to create the plant-pollinator interaction matrices which are the frequencies of species visits with each other.

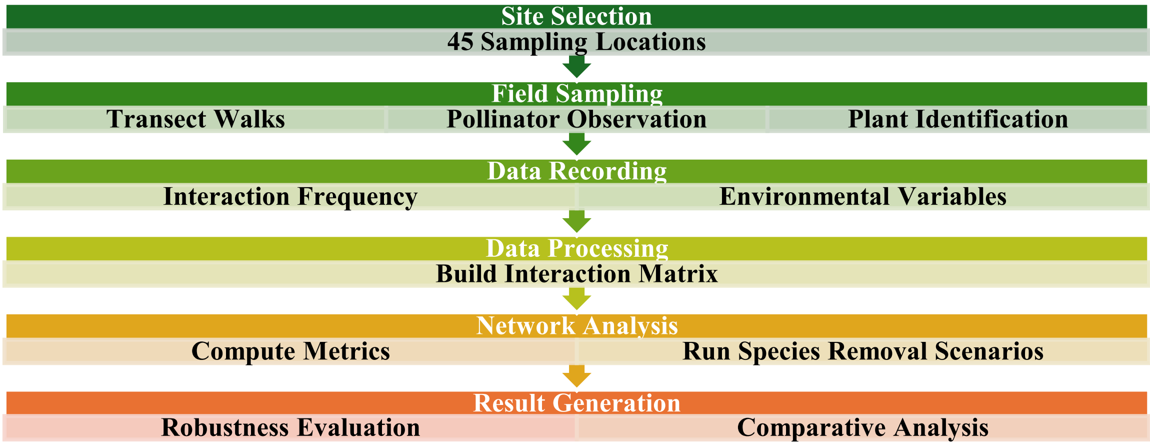


Figure 2: Workflow of Data Collection and Pollinator Network Analysis

This figure 2 provides the step-by-step methodological process that would be used in the study which includes site selection in 45 sampling sites then moving through systematic field sampling which includes transect walks, pollinator observations, and plant identification. It then records data of the frequency of interaction and environmental variables and then the data is processed to form interaction matrices. Network analysis then follows where key metrics are calculated and a scenario of species removal is simulated to result generation by evaluating the robustness and comparatively analyzing across the various landscape conditions.

Table 1: Framework of Field Sampling Design and Data Collection

| Parameter | Description | Measurement Frequency |
|---|---|---|
| Sampling Sites | 45 locations | Once (baseline) |
| Transect Length | 100 m | Per visit |
| Observation Period | 6 hours/day | Per sampling day |
| Sampling Seasons | 2 (dry and flowering seasons) | Annual |
| Pollinator Identification | Species/Morpho-species level | Continuous |
| Environmental Variables | Temperature, humidity, floral density | Per transect |

This table 1 is a summary of standardized procedures that were applied to gather ecological data in all the study sites in terms of sampling scale, duration of observation, seasonal coverage and environmental measurements. It brings out the uniformity of the field procedures used to record pollinator-plant interactions and other relevant conditions of the habitat so as to have credible and comparable data to build a network.

## Analysis Techniques for Assessing Pollinator Network Resilience

The bipartite interaction matrices were used to create pollinator networks with rows equal to plant species and columns equal to pollinators. The strength of link was quantified by the frequency of interactions. The ecological network analysis tools were used to compute major metrics of connectance, nestedness, modularity, and interaction evenness by performing network analysis. Experiments of simulated removal of species were measured as a test of resilience. Two conditions were used, random removal and targeted removal (degree of species number of interactions). In each case, species were removed in turn and the resulting secondary extinctions tabulated. The network robustness (R) was determined as the ratio of species that are present following repeated removals.

Other indicators were:

- Connectance (C): Fraction of interactions that were observed relative to the possible number of interactions.
- Nestedness (NODF): The extent to which specialists interact with specific groups of generalist associates.
- Modularity (Q): Degree of sub-grouping in the network.

Table 2: Essential Measures to assess the Pollinator Network Structure and Resilience

| Metric | Description | Purpose |
|---|---|---|
| Connectance | Proportion of realized interactions | Measures network density |
| Nestedness | Overlap of species interactions | Indicates redundancy |
| Modularity | Presence of distinct sub-networks | Identifies structural grouping |
| Robustness (R) | Resistance to species loss | Evaluates resilience |

This table 2 provides the major analytical measures to be applied to measure network structure and resilience based on connectance, nestedness, modularity, and robustness. All the metrics describe a particular dimension of ecological stability allow a systematic evaluation of the ecological network reaction to disturbances and to loss of species.

## Consideration of Variables such as Landscape Diversity and Habitat Quality

The diversity of the landscape was measured through the land-use classification in each study area (1 km 2). The field validation and the satellite imagery were employed to group the land into crop fields, grasslands, forest patches, and water bodies. The diversity of the landscape was expressed as a Shannon diversity index (H'). Indicators of habitat quality were measured based on floral richness and a percentage of vegetation cover and pesticide levels of exposure. The sites were classified into three, low, moderate, and high habitat quality. The abundance and frequency of interaction among these categories were then compared to ascertain its effect on the network structure.

Table 3: Indicators of Diversity and Quality of Habitat of the Landscape

| Variable | Measurement Method | Classification |
|---|---|---|
| Landscape Diversity | Shannon Index (H') | Low (<1.5), Medium, High (>2.5) |
| Floral Richness | Number of flowering species | Count per site |
| Vegetation Cover | Percentage ground cover | Low, Medium, High |
| Pesticide Exposure | Field survey and farmer input | Low, Moderate, High |

In this table 3, the environmental variables that are applied in the evaluation of the landscape composition and the habitat condition are given such as diversity indices, floral richness, vegetation cover, and pesticide exposure. Such indicators offer a foundation on which external ecological factors are studied and their impact on pollinator communities and the resilience of interaction networks in general.

The approach facilitates the assessment of the effect of landscape composition and habitat conditions on the resilience of pollinator networks based on the ecological network metrics and environmental variables.

## Results

### Findings on the Resilience of Pollinator Networks to Species Loss

The plant-pollinator networks showed different levels of resilience, depending on how species were removed and the structure of the network. When species were removed randomly, the networks remained highly connected with an average robustness of 0.76 (intermediate resilience to random damage). However, when we removed highly connected pollinators, the networks showed a decrease in robustness to 0.48, and secondary extinctions of connected plant species. Networks and interactions dropped at an increasing rate once around 30% of central pollinators were removed, suggesting the presence of a threshold leading to the network collapse. Networks with higher initial connectance and nested interactions suffered a slower decrease because the redundancy of interactions allowed functional connections to be maintained despite the removal of many species. Our findings demonstrate that network structure, in terms of connectance and nestedness, is important for buffering against environmental change.

### Identification of Key Species and Interactions within the Networks

Interaction network analysis found that there was a group of generalist pollinators that were overrepresented in network stability. These species had high degree centrality interacted with over 60% of the documented plant species. Their presence made the network available to various modules thereby avoiding being fragmented. The specialist species in contrast higher in interactions, helped in niche-specific pollination processes and added to biodiversity. There are also plant species that became centers, which provided numerous pollinators with the prolonged flowering duration and the abundance of nectar. Analysis of interaction strength indicated that about 25% of the species pairs represented more than 70% of the total visitation frequency, as a result of skewed distribution of ecological value. The elimination of these dominating interactions resulted in severe restructuring causing a decline in the overall evenness of interaction and network vulnerability.

## Comparison of Network Characteristics of Various Landscape Mosaics

We observed different characteristics in homogeneous and heterogeneous landscapes. The networks in these landscapes were more connected (0.41) and nested, facilitating more stable and redundant interactions. They also contained more species with an average of 28 pollinators per site (compared with 16 in homogeneous agricultural landscapes). But they were also less modular, suggesting more connected networks with more interaction links across species than in sub-clusters. This allows the interactions to be redistributed in the face of species extinctions. By contrast, simple landscapes showed higher modularity, with more fragmented species interactions and weaker interactions between sub-clusters, thus decreasing their resilience. Flower availability and diversity and environmental quality were tightly associated with increased interaction rates and increased resilience. A variety of vegetation and low pesticide use were associated with higher resilience and lower secondary extinctions.

### *Software Details*

Python based data analysis and ecological analysis libraries were used to implement the analysis. NetworkX and custom scripts were used to conduct network construction and compute metrics and NumPy, Pandas, and Matplotlib libraries were used to perform statistical analysis and visualization. QGIS facilitated the processing of spatial data and geospatial mapping and landscape classification.

### *Dataset Details*

The sample included the interaction records of 45 field sites with more than 3,200 described visitations of pollinators in 52 plant species and 68 species of pollinators. Species identity, frequency of interaction, geographic location and other environmental factors like the density of flora and the quality of habitat were listed in each record. Landscape classification features were also taken into the dataset, which made it possible to make comparative analysis among various mosaic structures.

## Performance Evaluation

The network resilience assessment performance was measured by various performance measures such as robustness (R), connectance (C), nestedness (N), and species persistence rate (SPR). These measures were calculated in case of random and specific removal of species to assess response of the system within different conditions of disturbance.

Table 4 that follows provides a comparison of major network measures in diverse species removal conditions and landscape conditions. It shows the effect of robustness, connectance, nestedness, and species persistence between random and targeted disturbance and among high and low diversity landscapes, which indicates that the type of disturbance and the complexity of the environment play an important role in overall network stability.

Table 4: Resilience of Pollinator Network Across Scenarios in Terms of Performance

| Scenario | Robustness (R) | Connectance (C) | Nestedness (N) | Species Persistence (%) |
|---|---|---|---|---|
| Random Removal | 0.76 | 0.39 | 0.62 | 81.5 |
| Targeted Removal | 0.48 | 0.31 | 0.44 | 56.2 |
| High Diversity Landscape | 0.82 | 0.41 | 0.68 | 87.3 |
| Low Diversity Landscape | 0.53 | 0.28 | 0.39 | 60.7 |

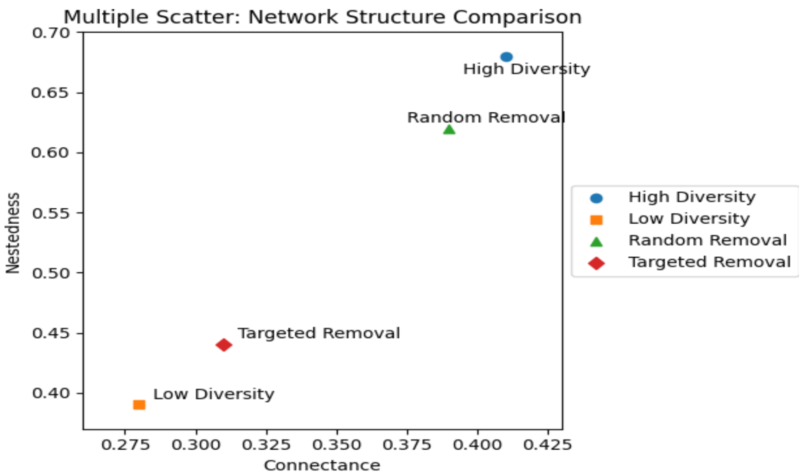


Figure 3: Network Under Various Conditions

The connectance and nestedness are compared in this scatter plot (Figure 3) in different situations, such as high and low diversity landscapes and random and targeted species removal. The distribution of the points shows that structurally complex networks tend to cluster at higher values, which implies greater resilience, whereas the simplified or disturbed networks go towards the lower interaction density and stability.

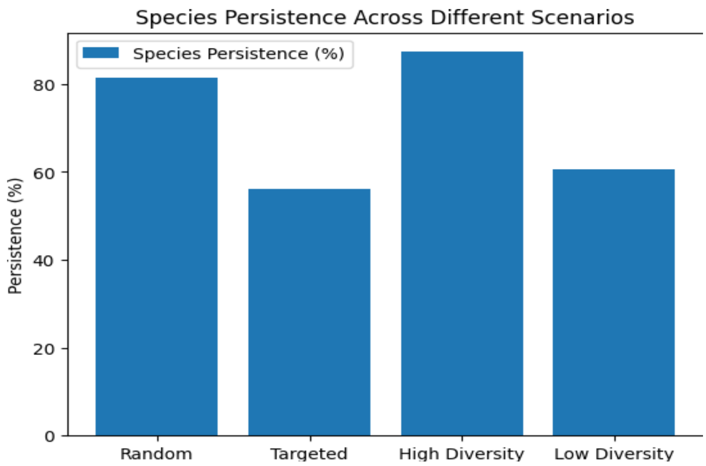


Figure 4: Species Survival at Disturbance Interactions

Figure 4 is a bar chart that gives the percentage of the species remaining in different conditions with the special focus to the comparison between the resilient and vulnerable network states. The ecological complexity also proves to be protective by higher persistence in different environments, and lower values in the case of particular removal show the severe effect of the loss of the significant pollination species.

### Ablation Study

The value of the critical factors affecting the network resilience was assessed through an ablation study. Three configurations were experimented; (i) the full model with all the variables, (ii) absence of landscape diversity and (iii) absence of weighting of interaction strength. The landscape diversity was found most robust (0.82) and elimination of landscape diversity decreased the robustness to 0.65, which underscores its importance. On the same note, neglecting the strength of interaction caused the decrease in nestness and an increase in the network fragmentation. These findings prove the point that both the environmental context and the dynamics of interactions are vital elements in the proper evaluation of pollinator network resilience.

## Discussion

The findings highlight the significance in a real-life situation of preserving diverse pollinator networks within agro-ecosystems that are structured. From a management perspective, the clear distinction in resilience between high-diversity and simplified landscapes suggests that farming practices should transition away from yield-oriented monocultures toward more heterogeneous land-use patterns. Directly, with the incorporation of semi-natural habitats, possible reduction of pesticide intensity and encouragement of floral diversity, the interaction redundancy is increased as well as species loss is buffered. Conservation should also focus on highly connected pollinators as vital nodes, meaning such pollinators should be protected to avoid ecological failure of the entire system. Moreover, connectivity and support pollinator movement through fragmented landscapes can be enhanced by adaptive land management approaches that include seasonal crop rotation and ecological corridors. In prospect, long-term temporal dynamics of these networks under climate variability and how emergent stressors, like the extreme weather events, contribute to species loss, need to be studied in future research. It is also open to the incorporation of innovative modelling schemes with the real-time ecological surveillance to predict tipping point in network collapse and steer a more robust agricultural planning.

## Conclusion

This paper gives a close evaluation of the response of pollinator networks to the experience of species loss in agricultural landscape mosaic, with the focus on the importance of structural complexity and species interactions. The results demonstrate that the network robustness is reduced by 38.6% during targeted species removal as opposed to 17.2% during random loss, emphasizing the overrepresentation of the effect of losing high connectivity pollinators. In the same way, the more diverse landscapes also had high values of robustness of up to 0.82 and species persistence rates of over 87.3% and simplified systems had much lower values of resilience and persistence reduced to about 60%.

These quantitative data are valid in supporting the argument that environmental context, as well as network structure, are mutually independent determinants of ecological stability. The need to preserve the pollinator network resilience is vital in conserving the biodiversity but also in ensuring the crop production and the sustainable agricultural viability in the long term. The research supports the argument that habitat heterogeneity, key species protection, and sustainable land management practices should be maintained to sustain ecological interactions. The current efforts should seek to reduce declines in the population of pollinators through immediate conservation measures such as habitat restoration and reduced chemical inputs. In the absence of these measures, the likelihood of network breakdown and resultant destruction of ecosystem services will keep rising, which is a huge problem to food security and environmental sustainability.

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