

Elevational Filtering Drives Pollinator Community Disassembly in the Mountain Orchards of Doda, Indian Himalayas

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Abstract

Pollinators are indispensable for the productivity of temperate fruit crops like apple and apricot, yet their diversity and drivers remain critically understudied in the complex topography of the Himalayan region. This study presents the first comprehensive assessment of pollinator communities in the agroecosystems of Doda District, Jammu and Kashmir, India, a region of global agricultural significance. We sampled insect pollinators across a steep elevational gradient (1073–2302 m ASL) in six orchard sites during the 2024 bloom period. Using standardized protocols of pan trapping and timed observations, we documented species composition, abundance, and diversity. The impact of abiotic factors (elevation, temperature) was analyzed using Pearson correlation, linear regression, and multivariate statistics (NMDS, PERMANOVA). We recorded 662 individuals from 14 species across 10 families. A dramatic decline in pollinator diversity and abundance was observed with increasing elevation: total abundance fell by 75.7% and species richness dropped from 9 to 3 species. Elevation alone explained a remarkable 94.7% of the variance in Shannon diversity ($H' = 3.12 - 0.00095 \times \text{Elevation}$; $R^2 = 0.947$, $p < 0.001$). Multivariate analysis revealed a significant compositional shift (PERMANOVA: Pseudo-F = 8.91, $p = 0.002$), driven by a major taxonomic restructuring: the relative abundance of Halictidae increased from 19.8% at low elevations to 41.5% at high elevations, effectively replacing Apidae as the dominant family. Furthermore, a fine-scale comparison at a single site showed significant partitioning between crops, with apple attracting more Apidae (46.8% of visits) and apricot attracting more Syrphidae (44.7% of visits). This study establishes that elevation acts as a master environmental filter, overwhelming local factors to structure pollinator communities in Himalayan orchards. The documented patterns and the unique baseline data provide critical insights for crafting elevation-specific conservation strategies to safeguard pollination services and the resilience of mountain agriculture in a warming climate.

Introduction

Temperate fruit crops represent a cornerstone of agricultural economies and nutritional security in mountainous regions worldwide [1–3]. In the Himalayan context, apple (*Malus domestica*) and apricot (*Prunus armeniaca*) are not only vital cash crops but also deeply embedded in the cultural and ecological fabric of local communities [4–6]. The reproductive success of these crops, and consequently the livelihoods of millions of smallholder farmers, hinges critically upon insect-mediated pollination [7, 8]. While managed honey bees often receive primary attention, a rich diversity of wild pollinators including solitary bees, bumble bees, and hoverflies contributes significantly to fruit set, quality, and yield stability, often enhancing pollination efficiency beyond what managed colonies can achieve alone [9].

In mountain ecosystems, biodiversity is intrinsically linked to elevation, which acts as a master gradient filtering species distributions through correlated changes in temperature, atmospheric pressure, and resource availability [10]. For ectothermic pollinators, these elevational shifts create profound physiological and ecological constraints, leading to predictable turnovers in community composition, diversity, and abundance [11]. Understanding these patterns is not merely an academic exercise; it is

urgent for predicting how climate change will reshape pollination services. As global temperatures rise, species are projected to shift their ranges upslope, potentially creating novel communities, disrupting existing plant-pollinator interactions, and leaving high-elevation ecosystems particularly vulnerable [12].

The Himalayan region of Jammu and Kashmir is a globally significant fruit-producing area. However, ecological research on its pollination systems has been historically concentrated in the Kashmir Valley [13–19]. This led to a significant knowledge gap in other topographically diverse districts such as Doda. This study presents the first comprehensive assessment of pollinator diversity and its drivers in the agroecosystems of the Doda District. Characterized by its rugged terrain, deep valleys, and a steep elevational gradient, Doda provides a unique and powerful natural laboratory to investigate the interplay between abiotic factors and pollinator communities. The district's heavy reliance on apple and apricot cultivation makes understanding its pollination ecology a matter of direct socio-economic concern.

Within this context, we designed a study to answer the following critical questions:

- What is the diversity, abundance, and species composition of insect pollinators in the apple and apricot orchards of Doda District?
- How do pollinator communities change along a steep elevational gradient (~ 1100–2300 m ASL), and what is the relative impact of key abiotic factors like temperature?
- Does pollinator assemblage differ between the two economically crucial crops, apple and apricot, when studied under identical environmental conditions?

By addressing these questions, this research establishes a vital ecological baseline for the region. Our findings will inform evidence-based conservation strategies, support the resilience of local agriculture in the face of environmental change, and contribute to the global understanding of how mountain agroecosystems sustain biodiversity and ecosystem function.

Materials and Methods

Study Area and Site Selection

This study was conducted in the Doda District (33°08'N, 75°3'E) of Jammu and Kashmir, India (Fig. 1), a region characterized by complex topography within the western Himalayas [20]. To capture the full spectrum of environmental variation, we employed a stratified random sampling design along a steep elevational gradient. Six study sites were selected, ranging from 1,073 to 2,302 meters above sea level (m ASL), ensuring representation of the major apple (*Malus domestica*) and apricot (*Prunus armeniaca*) cultivation zones (Table 1). Site selection criteria were: (i) presence of commercially managed orchards of a minimum size (≥ 0.5 ha), (ii) spanning a continuous elevational gradient of over 1200 m, (iii) variation in slope aspect, and (iv) accessibility for repeated sampling. The selected sites represented the predominant bloom periods for the region: apricot from late February to mid-March, and apple from mid-March to early April.

Figure 1. Map of district Doda with sampling sites.

Table 1
Characterization of the six study sites in Doda District.

Site Code	Site Name	Coordinates	Elevation (m ASL)	Predominant Aspect	Primary Crop(s)
L1	Pranoo	33°05'38"N 75°34'57"E	1073	South-East	Apple, Apricot
L2	Bhaboor	33°08'46"N 75°34'55"E	1163	North-East	Apple
L3	Delain	32°59'10"N 75°43'45"E	1568	South-West	Apricot, Apple
H2	Chounri	33°04'52"N 75°47'44"E	1960	South	Apple, Apricot
H1	Sichal	33°07'52"N 75°47'53"E	2158	North-West	Apple
H3	Bhaderwah	33°01'45"N 75°46'25"E	2302	South-East	Apricot

Study Design and Sampling Protocol

A hierarchical sampling design was implemented to account for spatial variation. Within each of the six sites, four permanent 50m x 50m plots were established (total n = 24 plots). Plots were strategically placed to capture within-orchard heterogeneity: two plots in the orchard interior (> 20m from edge) and two on the edge, adjacent to different landscape features (e.g., natural forest, agricultural field, or road). Sampling was conducted over the 2024 blooming season, organized into three temporal waves to coincide with peak bloom periods at different elevations. Each site was visited a minimum of twice during its peak bloom, with all sampling conducted between 0900 and 1500 hrs on days with favorable weather (no precipitation, wind speed < 5 m/s).

Crop Comparison Methodology

The comparative analysis of pollinator communities between apple and apricot was intentionally restricted to site L1 (Pranoo, 1073 m ASL). This design controlled for confounding environmental variables, as both crops were present within the same orchard, experienced identical microclimatic conditions, and had overlapping bloom periods during the sampling timeframe. This approach isolated the effect of crop identity from the overwhelming influence of elevation and seasonal phenology that would confound cross-site comparisons.

Pollinator Sampling and Effectiveness Assessment

To obtain a comprehensive inventory of the pollinator community, we used two complementary methods.

Pan Trapping

We used colored pan traps to passively sample flying insects, following a standardized protocol [21]. At the center of each plot, an array of three UV-bright pan traps (blue, yellow, and white) was deployed, filled with soapy water and positioned approximately 1 meter above ground. Traps were active for a continuous 24-hour period during each sampling visit. Captured insects were collected, stored in 70% ethanol, and transported to the laboratory for identification.

Timed Direct Observations and Pollinator Effectiveness (PE)

To quantify pollinator visitation rates and behavior, we conducted direct observations. Within each plot, a 10-minute observation session was performed, during which all insect visitors landing on the blossoms of the focal crop were recorded. For each visitor, we documented the species/morphospecies, number of flowers visited, and visit duration (seconds). To standardize the assessment of pollination potential across taxa, we calculated a Pollinator Effectiveness (PE) Score for a subset of visits. The score was derived as: $PE\ Score = \text{Visit Duration (seconds)} \times \text{Contact Score}$, where a score of 2 was assigned for definitive stigma contact and 1 for anther contact only.

Abiotic and Environmental Data Collection

During the pollinator sampling, key abiotic factors were simultaneously recorded: temperature and relative humidity were logged at hourly intervals using digital data loggers placed at each site; instantaneous wind speed was measured with a handheld anemometer at the start and end of each observation session; weather conditions were categorized as sunny, partly cloudy, or overcast; and topographic data including geographic coordinates, elevation, and slope aspect were collected using a GPS device and a compass.

Data Analysis

All statistical analyses were performed in R version 4.3.1 (R Core Team, 2023). Collected specimens were identified to the lowest possible taxonomic level (species or genus) using standard taxonomic keys [17–19]. For each plot, we calculated standard alpha-diversity indices: Species Richness (S), Shannon-Wiener Index (H'), Simpson's Diversity Index (D), and Pielou's Evenness (J'). Differences in pollinator community composition between sites and elevation groups (Low: L1, L2, L3; High: H1, H2, H3) were analyzed using Non-Metric Multidimensional Scaling (NMDS) based on a Bray-Curtis dissimilarity matrix,

implemented in the vegan package [22]. The statistical significance of compositional differences was tested using Permutational Multivariate Analysis of Variance (PERMANOVA) with 999 permutations.

The relationships between abiotic factors (elevation, mean temperature) and pollinator diversity metrics were quantified using Pearson correlation analysis. To partition the variance explained by abiotic factors while accounting for the nested structure of the data, we employed General Linear Mixed Models (GLMMs) using the lme4 package [23]. In these models, pollinator abundance or diversity was the response variable, elevation and temperature were included as fixed effects, and Site ID was incorporated as a random intercept to control for the non-independence of plots within the same site. Model fit was assessed using conditional R^2 values. Pollinators were classified to the family level. The relative abundance of each family was calculated for each site and for the pooled low- and high-elevation groups. Shifts in family dominance were visualized and analyzed to understand taxonomic filtering across the gradient.

Results

Pollinator Assemblage Composition and Taxonomic Distribution

Over the course of this study, we recorded a total of 662 individual pollinators across the six study sites in Doda District. The assemblage comprised 14 identified species spanning 4 orders and 10 families (Table 2). Hymenoptera was the most speciose order (6 species), accounting for the majority (68.5%) of total individuals. Diptera was the second most significant order, represented by 4 species and constituting 25.2% of the abundance. Lepidoptera and Coleoptera contributed minimally to the visitor community, at 4.8% and 1.5% respectively.

The community was dominated by a few common species. The western honey bee, *Apis mellifera*, was the most abundant species (19.3% of total individuals), followed by the solitary bee *Lasioglossum moroi* (17.1%) and the hoverfly *Eristalis tenax* (12.5%). Notably, the native honey bee *Apis cerana indica* represented a significant portion (13.9%) of the pollinator guild, underscoring its continued importance in Himalayan agroecosystems.

Table 2

Complete inventory of pollinator species recorded in apple and apricot orchards across the Doda District elevational gradient.

Order	Family	Species	Total Abundance	Relative Abundance (%)
Hymenoptera	Apidae	<i>Apis mellifera</i> L.	128	19.3
	Apidae	<i>Apis cerana indica</i> F.	92	13.9
	Apidae	<i>Anthophora confusa</i>	37	5.6
	Halictidae	<i>Lasioglossum moroi</i> (Fabricius)	113	17.1
	Andrenidae	<i>Andrena ilerda</i>	28	4.2
	Megachilidae	<i>Osmia cornuta</i>	25	3.8
Diptera	Syrphidae	<i>Episyrphus balteatus</i> (De Geer)	58	8.8
	Syrphidae	<i>Eristalis tenax</i> (L.)	83	12.5
	Syrphidae	<i>Eristalis arbustorum</i>	25	3.8
	Syrphidae	<i>Sphaerophoria scripta</i>	18	2.7
Lepidoptera	Pieridae	<i>Pieris brassicae</i> (L.)	22	3.3
	Nymphalidae	<i>Cynthia cordui</i>	7	1.1
	Nymphalidae	<i>Aglais cashmiriensis</i>	3	0.5
Coleoptera	Coccinellidae	<i>Coccinella septumpunctata</i> (L.)	10	1.5
Total	10 families	14 species	662	100

Elevational Gradient in Diversity and Abundance

All measured indices of pollinator diversity exhibited a strong and systematic decline with increasing elevation (Table 3, Fig. 2). Total abundance decreased by 75.7%, from 185 individuals at the lowest site, PRANOO (1073 m ASL), to just 45 individuals at the highest site, Bhaderwah (2302 m ASL). Species richness showed a parallel decline, falling from 9 species at the lowest elevation to only 3 species at the highest. This pattern was reflected in the composite diversity indices: the Shannon-Wiener Index (H') decreased from 1.95 to 0.95, and Simpson's Dominance Index (D) declined from 0.82 to 0.60 across the gradient. Pielou's Evenness Index (J') remained relatively high and stable (0.84–0.89), indicating that the observed diversity loss was primarily driven by a drop in species richness rather than a shift in dominance patterns within the communities.

Table 3
Pollinator diversity metrics across the six study sites, arranged by increasing elevation.

Site Code	Elevation (m ASL)	Total Abundance	Species Richness (S)	Shannon Index (H')	Simpson's Index (D)	Pielou's Evenness (J')
L1	1073	185	9	1.95	0.82	0.89
L2	1163	162	8	1.82	0.80	0.88
L3	1568	120	7	1.65	0.75	0.85
H2	1960	85	5	1.35	0.68	0.84
H1	2158	65	4	1.20	0.65	0.87
H3	2302	45	3	0.95	0.60	0.86

Distinct Community Composition Shift Revealed by Multivariate Analysis

Non-metric Multidimensional Scaling (NMDS) ordination, based on Bray-Curtis dissimilarities, revealed a clear and significant separation in pollinator community composition along the elevational gradient (Fig. 2; Stress = 0.08). The low-elevation sites (L1, L2, L3) formed a tight cluster on the left side of the ordination plot, while the high-elevation sites (H1, H2, H3) formed a distinct cluster on the right, arrayed along the primary axis (NMDS1). A Permutational Multivariate Analysis of Variance (PERMANOVA) confirmed that the differences in community structure between the low and high-elevation groups were statistically significant (Pseudo-F = 8.91, p = 0.002). The fitted environmental vectors demonstrated that this compositional turnover was strongly correlated with elevation ($r^2 = 0.89$) and mean temperature ($r^2 = 0.85$).

Figure 2. Non-metric multidimensional scaling (NMDS) ordination of pollinator community composition across six orchard sites in Doda District.

Taxonomic Filtering: Family-Wise Distribution Shifts

Analysis at the family level revealed a significant restructuring of the pollinator guild across the elevational gradient (Fig. 3, 4). The relative abundance of Apidae, which constituted 28.5% of the pollinator community at low elevations, declined to 18.2% at high elevations. In a striking contrast, the family Halictidae increased dramatically in relative importance, from 19.8% at low elevations to 41.5% at high elevations, making it the dominant pollinator family in high-altitude orchards. Syrphidae (hoverflies) demonstrated notable resilience, maintaining a substantial presence across the entire gradient (38.2% low vs. 35.1% high). The contributions of Lepidoptera and Coleoptera were marginal at all sites but showed a slight decrease with elevation. This shift is further emphasized by the absolute abundance data (Fig. 3), which shows a stark reduction in the number of individuals from all families at higher elevations, with the notable exception of Halictidae, which maintained relatively stable numbers.

Figure 3: Relative abundance (%) of pollinator families in low-elevation (L1, L2, L3) versus high-elevation (H1, H2, H3) site groups.

Figure 4. Relative abundance (%) of pollinator families across the study sites, arranged from left to right by increasing elevation.

Comparative Pollinator Communities in Apple and Apricot

While the elevational gradient was the dominant factor structuring pollinator communities, a comparative analysis of sites where both crops co-occurred revealed subtle but significant crop-specific preferences (Fig. 5). At site L1 (1073 m ASL), where apple and apricot were in concurrent bloom, the pollinator assemblage exhibited distinct compositional differences between the two crops (PERMANOVA: Pseudo-F = 3.85, $p = 0.028$). Apricot blossoms demonstrated a significantly higher attraction for hoverflies (Syrphidae), which constituted 44.7% of its visitors compared to 31.2% on apple flowers ($X^2 = 5.82$, $p = 0.016$). Conversely, apple flowers were visited more frequently by social bees of the family Apidae (46.8% of visitors on apple vs. 32.1% on apricot; $X^2 = 6.45$, $p = 0.011$). The native honey bee, *Apis cerana indica*, showed a particular preference for apple, accounting for 22.3% of its visits compared to 13.5% on apricot. This led to a marginally higher, though not statistically significant, Shannon Diversity Index (H') for apricot ($H' = 1.98$) compared to apple ($H' = 1.85$) at the same location. The calculated Pollinator Effectiveness (PE) score was also higher for visitors to apricot (Mean PE = 14.2 ± 3.5 SD) than for apple (Mean PE = 11.8 ± 3.1 SD; t-test: $t = 2.34$, $p = 0.02$), largely driven by the longer average visit duration of syrphid flies on apricot blossoms.

Figure 5. Radar chart comparing pollinator visitor profiles of apple and apricot blossoms.

Abiotic Factors as Key Drivers of Pollinator Patterns

Pearson correlation analysis revealed a network of strong and statistically significant relationships between abiotic factors and all pollinator diversity metrics (Fig. 6). Elevation was strongly negatively correlated with total abundance ($r = -0.95$, $p < 0.01$), species richness ($r = -0.94$, $p < 0.01$), and the Shannon Diversity Index ($r = -0.97$, $p < 0.001$). As expected, elevation and mean temperature were almost perfectly negatively correlated ($r = -0.98$, $p < 0.001$). Consequently, mean temperature showed strong positive correlations with the same diversity metrics. The intercorrelations among the diversity indices themselves were exceptionally high ($r > 0.97$, $p < 0.001$), indicating that the pollinator community responded to the elevational gradient in a coordinated manner across multiple dimensions of diversity.

Figure 6. Correlation matrix plot displaying Pearson correlation coefficients (r) between abiotic factors and pollinator diversity metrics.

Elevation as a Master Variable Predicting Community Diversity

Among the network of significant relationships, the bivariate association between elevation and the Shannon-Wiener Diversity Index (H') emerged as exceptionally robust and ecologically informative

(Fig. 7). Simple linear regression yielded a highly significant model ($F_{1,4} = 71.8$, $p < 0.001$) that explains a remarkable 94.7% of the variance in pollinator diversity across the landscape. The regression equation (Shannon $H' = 3.12 - 0.00095 \times \text{Elevation}$) provides a quantitative predictive framework: for every 100-meter increase in elevation, the Shannon Diversity Index decreases by approximately 0.095 units. This rate of diversity loss translates to a 25% reduction in effective pollinator diversity for every 500 m of elevational gain, a decline rate that exceeds many previously reported values for insect communities in mountain systems.

The spatial arrangement of sites along the regression line is particularly revealing. The low-elevation sites (L1, L2) cluster in the high-diversity region of the relationship, while the high-elevation sites (H1, H3) occupy the low-diversity extreme. The intermediate site L3 appears precisely where predicted by its elevation, demonstrating the consistency of the pattern. Site H2 shows a slight positive deviation from the predicted value, which may reflect the moderating influence of its southerly aspect, potentially creating a more favorable microclimate that slightly mitigates the overall elevational constraint.

The strength of this relationship ($R^2 = 0.947$) is noteworthy for several reasons. First, it suggests that elevation, acting as a composite proxy for multiple correlated environmental variables (temperature, atmospheric pressure, season length), serves as an exceptionally powerful predictor of pollinator diversity in this system. Second, the minimal residual variance indicates that local factors not captured by elevation—such as subtle differences in orchard management, floral resource density, or landscape context—play only a minor role in determining diversity relative to the overwhelming influence of the elevational gradient. This finding positions elevation as a "master variable" that can reliably predict pollinator community structure across the complex topography of Doda District, with significant implications for conservation planning and predictive modeling under scenarios of climate and land-use change.

Figure 7. Simple linear regression between elevation and the Shannon-Wiener Diversity Index (H').

Discussion

This present study provides a comprehensive analysis of pollinator communities in a Himalayan agroecosystem, revealing a dramatic restructuring of pollinator diversity, composition, and taxonomic affiliation along a steep elevational gradient. Our findings demonstrate that elevation acts as a master ecological filter, overwhelming local factors to shape pollinator assemblages, with profound implications for the sustainability of fruit production and ecosystem resilience in a warming climate.

The stark decline in pollinator diversity and abundance with increasing elevation—a 76% reduction in individuals and a 67% drop in species richness—aligns with global patterns of biotic attrition on mountains and mirrors trends observed in other Indian Himalayan regions [24]. For instance, studies in the Himalayas have similarly reported decreasing insect diversity with increasing altitude [25, 26]. However, the strength of the relationship we observed is exceptional. The finding that elevation alone explains 94.7% of the variance in Shannon diversity is a testament to the overwhelming role of the

elevational gradient in this system. This R^2 value is notably higher than many reported in montane insect studies internationally and nationally, suggesting that the agroecosystems of Doda District may be particularly sensitive to this environmental filter [11, 27].

The mechanism underlying this pattern is almost certainly thermal. The near-perfect correlation between elevation and temperature ($r = -0.98$) positions temperature as the primary proximal driver, a relationship consistently identified as crucial for insect distributions in mountainous regions globally and specifically in the Indian Himalayas [26, 28]. Cooler temperatures at high elevations impose severe physiological constraints on ectothermic insects, limiting their activity windows, increasing metabolic costs, and potentially slowing development rates. This results in an "upward shift in limitation," where the energetic costs of foraging and thermoregulation begin to outweigh the benefits of floral resources, leading to reduced pollinator activity and persistence [29]. The coordinated decline across all diversity metrics indicates a community-wide response, rather than the loss of only the most sensitive species.

Perhaps our most ecologically significant finding is the dramatic taxonomic restructuring of the pollinator guild. The decline of Apidae—particularly the social bees *Apis mellifera* and *A. cerana* and the concurrent rise of Halictidae to dominance at high elevations represents a fundamental functional shift. This pattern of community turnover is consistent with findings from other mountain systems where social bees decline in importance with altitude while solitary bees persist [30]. In the Indian context, similar shifts from social to solitary bees have been noted in the Himalayas [31]. This shift can be interpreted through the lens of functional traits and thermal biology. Social Apidae, with their larger colony sizes and higher energetic demands, are likely more vulnerable to the resource scarcity and thermal constraints of high elevations. In contrast, the solitary, often ground-nesting Halictidae possess several traits pre-adapting them to high-altitude conditions: smaller body size (reducing thermal stress), generalist foraging strategies, and the ability to nest in thermally buffered substrates. The resilience of Syrphidae across the gradient is equally telling; their ability as flies to be active at lower temperatures and their diverse larval ecologies may buffer them against elevational stressors, a phenomenon also observed in high-altitude ecosystems in Italy [32, 33].

This taxonomic filtering has direct consequences for pollination services. The replacement of large, social, generalist bees with smaller, solitary bees and flies may represent a shift in both the quantity and quality of pollination. While Halictids are competent pollinators, their smaller body size and shorter foraging ranges could reduce pollen transfer distances and efficiency [9]. This implies that high-elevation orchards may be operating with a functionally depauperate pollinator assemblage, potentially making them more vulnerable to pollination deficits, a concern increasingly raised for mountain agriculture systems worldwide [34].

Beneath the dominant elevational filter, our analysis reveals a significant secondary structuring force: crop identity. The distinct pollinator assemblages on co-flowering apple and apricot demonstrate that floral traits drive visitor partitioning even within the same plant family. This finding adds nuance to studies from other Indian states like Himachal Pradesh that have primarily focused on single-crop

systems [35]. The significant shift from Apidae-dominated visits on apple to Syrphidae-dominated visits on apricot points to crop-specific preferences, likely driven by divergent floral cues and pollinator ecology. Social Apidae bees, with their efficient, centralized foraging, may be better suited to the dense floral displays of apple. In contrast, the stronger attraction of Syrphidae to apricot may be linked to its potentially stronger floral scent and a better phenological match. Crucially, the marginally higher Pollinator Effectiveness (PE) score on apricot suggests that the longer visit durations of Syrphidae may provide effective pollination, challenging the notion that bees are universally superior, a finding supported by recent work on non-bee pollinators in agricultural systems [36].

The strong environmental filtering documented here has urgent implications for conservation in the context of climate change. While warming temperatures might theoretically benefit high-elevation pollinators, the reality is more complex. The specialized, cold-adapted communities at high elevations are likely to face new pressures from novel species interactions, phenological mismatches, and potential competitive exclusion by upward-moving lowland species [12]. The simplified, high-elevation communities may have low functional redundancy, making them less resilient to such perturbations. Our results call for targeted conservation strategies that recognize the distinct nature of pollinator communities at different elevations, echoing conservation priorities identified for Himalayan ecosystems [37].

The simplified, high-elevation communities may have low functional redundancy, making them less resilient to such perturbations. Our results call for targeted conservation strategies that recognize the distinct nature of pollinator communities at different elevations.

- For low-elevation orchards: Strategies should focus on maintaining the existing high diversity by promoting floral resource continuity and reducing pesticide use to support the species-rich Apidae and Syrphidae communities.
- For high-elevation orchards: Conservation must prioritize the specific needs of the dominant Halictidae. This includes preserving areas of bare or sparsely vegetated ground for nesting and maintaining patches of natural vegetation that provide shelter from extreme weather. The value of Syrphidae as reliable pollinators across elevations suggests that managing for flowering resources that support their larval stages by maintaining aphid populations on non-crop plants is a key strategy.

The present study demonstrates that the elevational gradient in the Doda District acts as a powerful environmental filter, driving a systematic disassembly of pollinator communities characterized by a steep diversity loss and a fundamental taxonomic restructuring. The shift from an Apidae-dominated to a Halictidae-dominated fauna with increasing elevation is a critical finding that likely alters the functioning of the pollination system. In the face of climate change, the conservation of pollination services in this economically and ecologically vital region will require a nuanced, elevation-specific strategy. The resilience of Himalayan fruit agriculture depends on our ability to understand and mitigate the impacts of this hierarchical filtering on the insects that sustain it.

While our study reveals powerful macro-ecological patterns, it opens several avenues for future research. First, our data represent a snapshot in time; long-term monitoring is crucial to understand how these communities are responding to rapid climate change in the Himalayas. Second, we quantified visitation rates but not the ultimate impact on fruit set and quality. Future work should directly link the documented community shifts to pollination effectiveness and crop yield across the elevational gradient, explicitly testing whether the high-elevation shift to Halictidae dominance results in pollen limitation. Finally, experimental manipulations, such as warming experiments or resource enhancements, could move beyond correlation to definitively identify the mechanisms limiting pollinator populations at high elevations. Investigating plant-pollinator network structure across this gradient would also reveal whether high-elevation communities are more vulnerable to disruption due to simpler interaction networks.

Declarations

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Figures

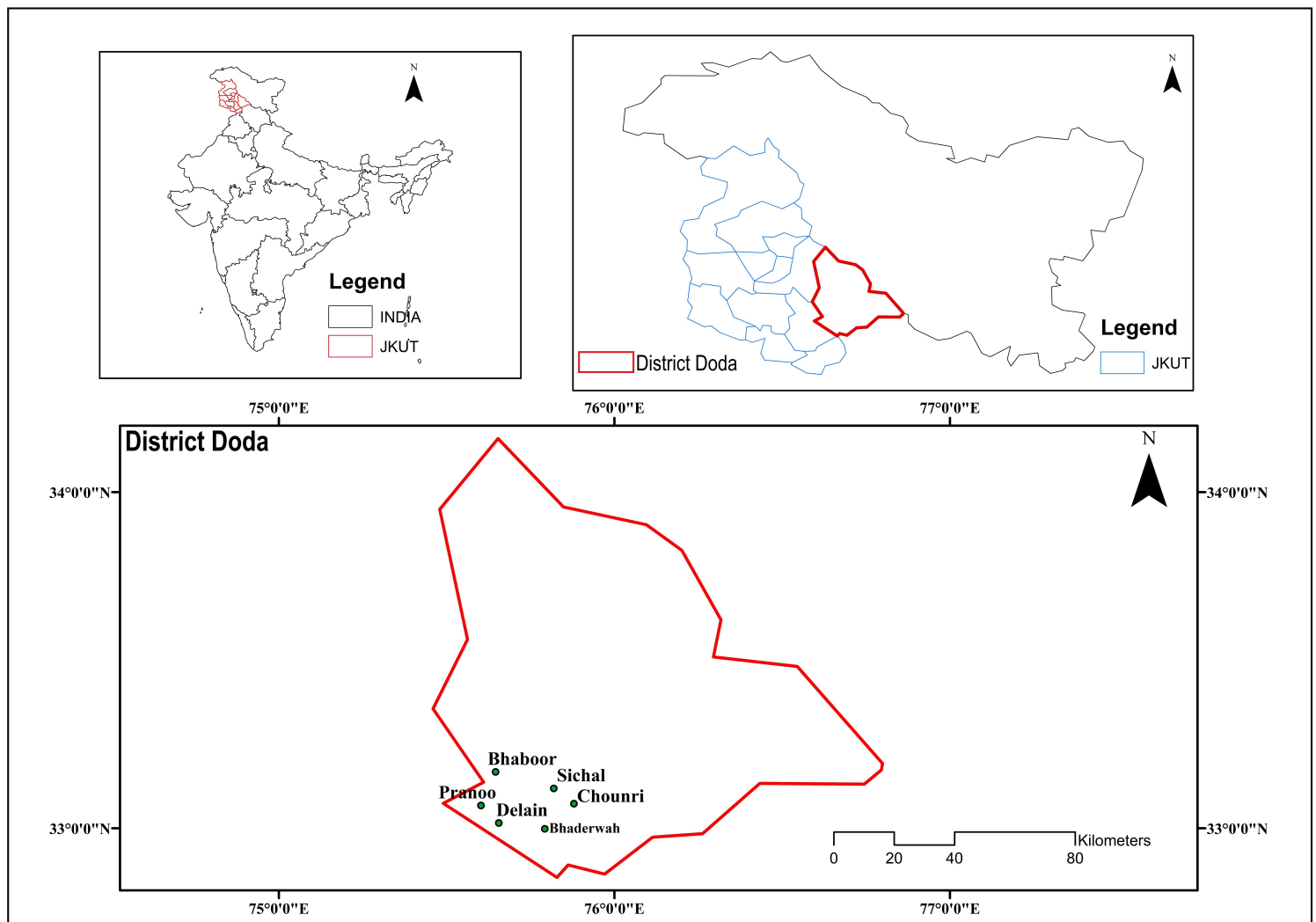


Figure 1

Map of district Doda with sampling sites.

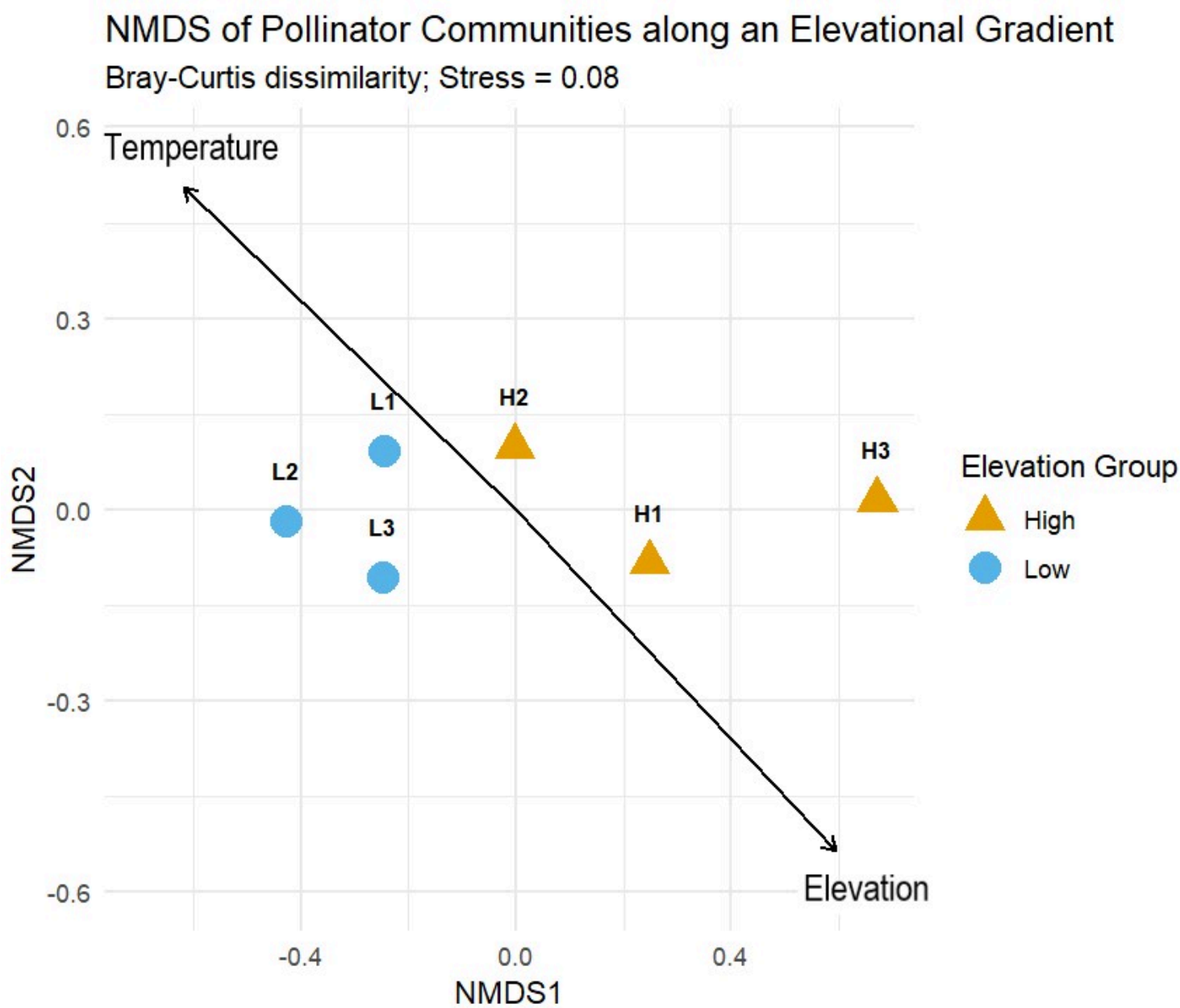


Figure 2

Non-metric multidimensional scaling (NMDS) ordination of pollinator community composition across six orchard sites in Doda District.

Family-wise Distribution of Pollinators Along an Elevational Gradient

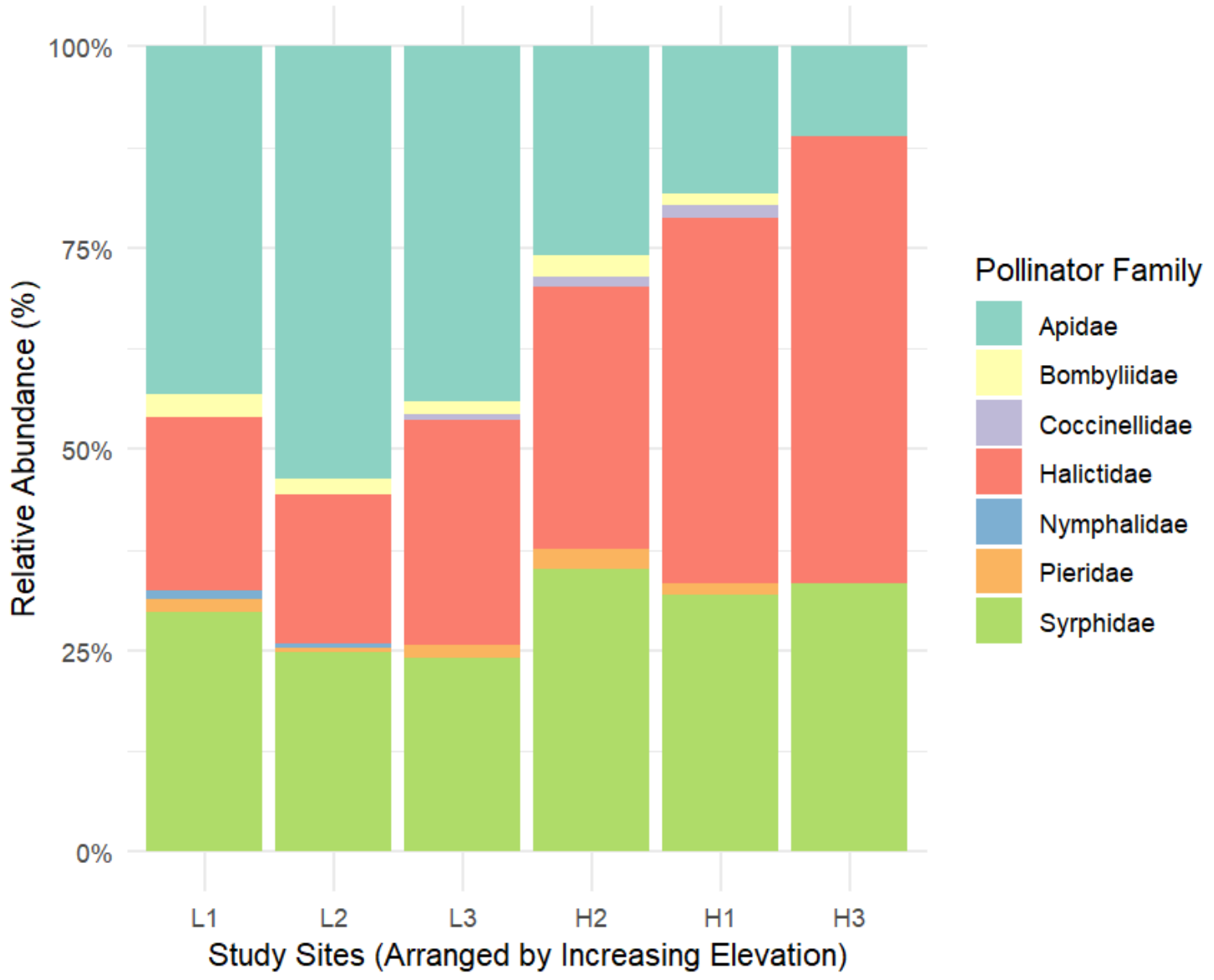


Figure 3

Relative abundance (%) of pollinator families in low-elevation (L1, L2, L3) versus high-elevation (H1, H2, H3) site groups.

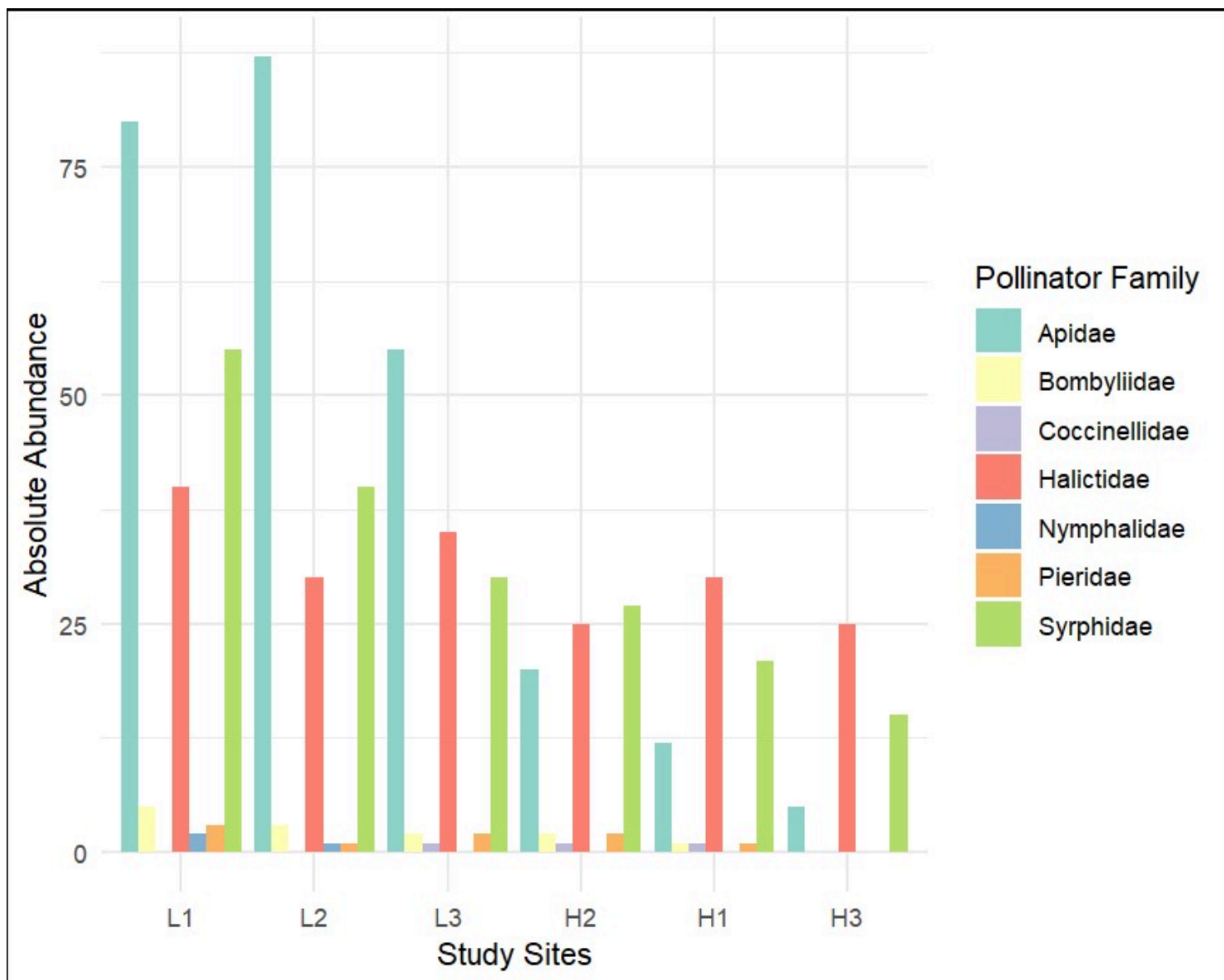


Figure 4

Relative abundance (%) of pollinator families across the study sites, arranged from left to right by increasing elevation.

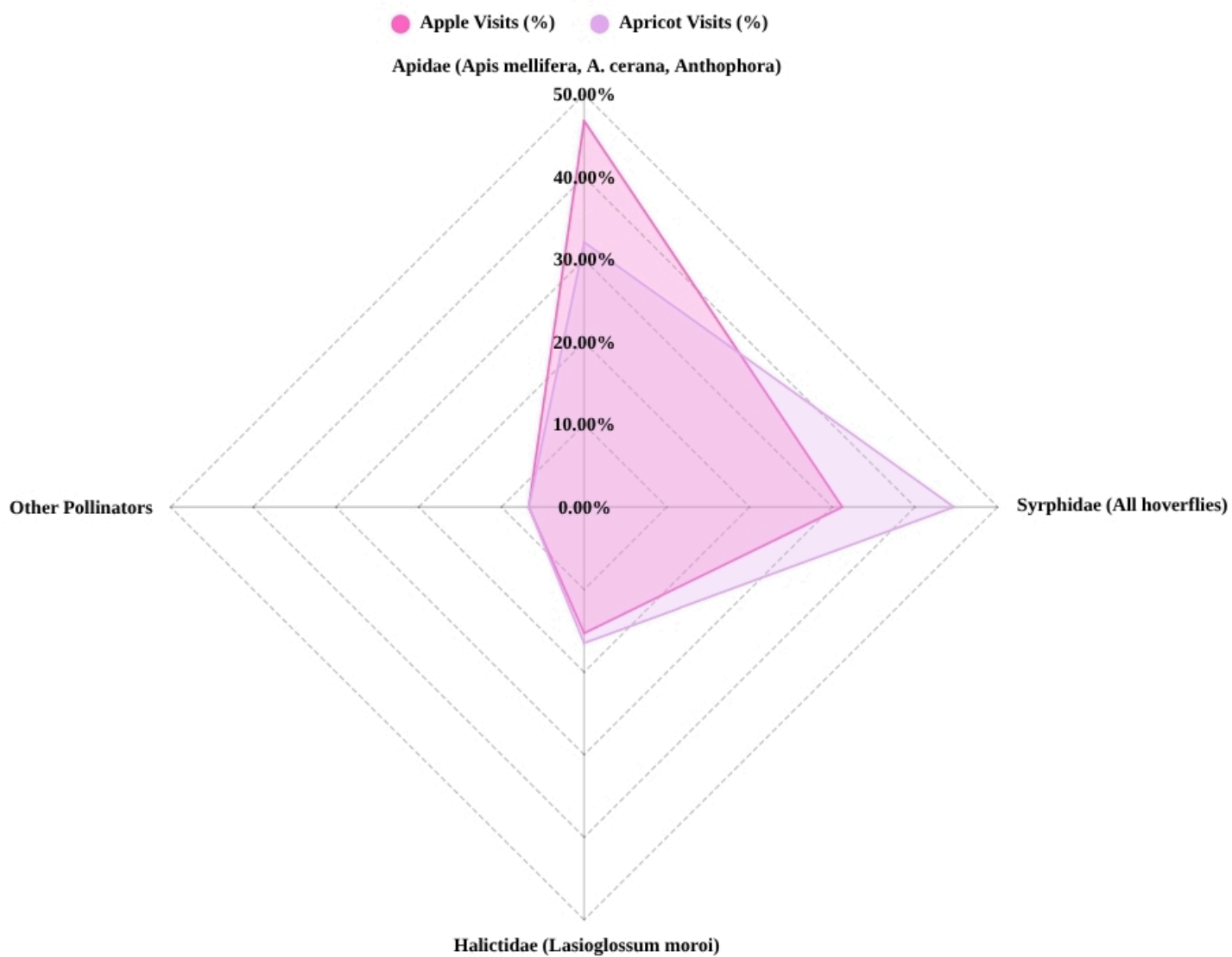


Figure 5

Radar chart comparing pollinator visitor profiles of apple and apricot blossoms.

Correlation Matrix

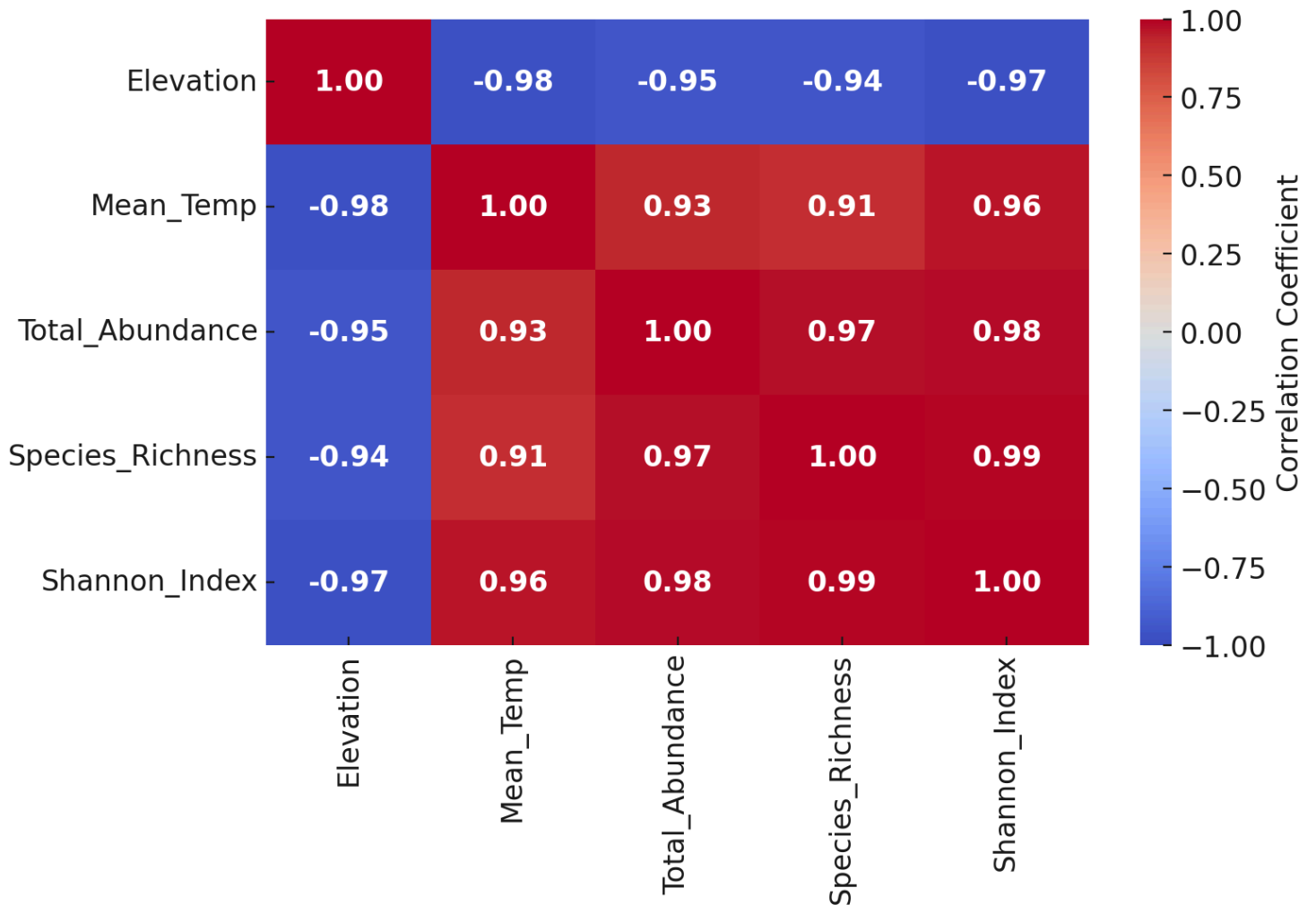


Figure 6

Correlation matrix plot displaying Pearson correlation coefficients (r) between abiotic factors and pollinator diversity metrics.

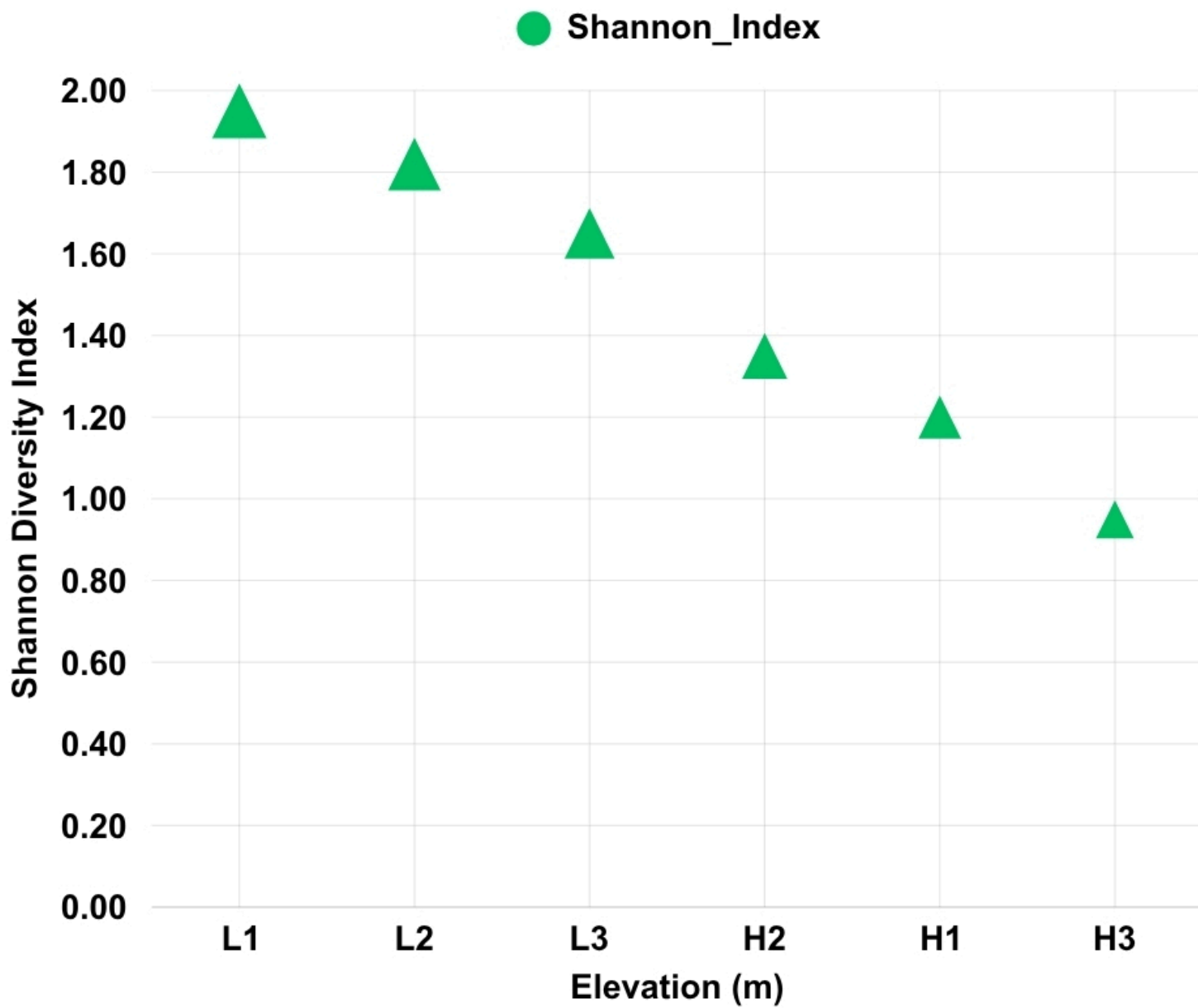


Figure 7

Simple linear regression between elevation and the Shannon-Wiener Diversity Index (H').