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Environmental drivers of avian biodiversity change in semi-arid agricultural landscapes

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Abstract
Semi-arid agricultural regions face significant pressures from land-use intensification and climate variability, yet the relative importance of environmental drivers on avian community composition remains poorly understood. This study examined how landscape structure, soil moisture, and agricultural management practices influence bird diversity and abundance in the Rajasthan semi-arid region of India. We conducted point-count surveys across 48 agricultural sites stratified by farming intensity (conventional monoculture, integrated pest management, and organic cultivation) during monsoon and post-monsoon seasons over two years (2020–2022). Using generalized linear mixed models, we quantified relationships between avian species richness, abundance, and environmental variables while controlling for temporal and spatial autocorrelation. Bird species richness was significantly higher in organic farming systems (mean ± SD: 18.3 ± 4.2 species per site) compared to conventional agriculture (11.7 ± 3.8 species; $p < 0.001$). Landscape heterogeneity, measured as the number of habitat patches within 500 m radius, explained 52% of variance in species richness ($R^2 = 0.52$, $p < 0.001$). Soil moisture and vegetation cover were significant predictors of abundance in granivorous and insectivorous guilds respectively. Our findings demonstrate that landscape management practices favoring habitat diversity substantially enhance avian conservation value in semi-arid agroecosystems. Results suggest that transitioning to diversified farming systems could provide dual benefits of ecosystem service provision and biodiversity enhancement without compromising agricultural productivity. This research contributes critical knowledge for developing evidence-based agro-conservation strategies in water-stressed regions and provides a methodological framework applicable to similar ecosystems globally.

Keywords: Semi-arid agriculture, avian biodiversity, landscape heterogeneity, farmland management, species richness, habitat connectivity, climate vulnerability

Introduction

Semi-arid agricultural landscapes represent critical interfaces between human livelihoods and ecosystem functioning, supporting approximately 2 billion people globally while maintaining significant ecological value [1]. These regions are characterized by low and erratic rainfall, high temperature variability, and shallow soils, creating challenging conditions for both agricultural productivity and biodiversity conservation. The agricultural expansion in semi-arid zones has intensified over the past three decades, driven by population growth and market demands, resulting in extensive habitat fragmentation and reduced landscape heterogeneity [2, 3].

Avifauna serve as particularly useful bio indicators of environmental change due to their high trophic position, sensitivity to habitat alterations, and accessibility for monitoring [4]. Birds provide essential ecosystem services in agricultural landscapes including pest control, pollination, and seed dispersal, yet their populations have declined significantly in intensively managed agricultural regions worldwide [5, 6]. In semi-arid agroecosystems, avian communities face compounded pressures from climatic variability, reduced water availability, and conversion of traditional polyculture systems to resource-intensive monocultures. Understanding the environmental mechanisms driving bird community responses is essential for developing sustainable agricultural practices that maintain both productivity and ecological function.

Previous research in semi-arid regions has documented relationships between individual environmental variables and bird populations, yet holistic assessments of multiple drivers simultaneously remain limited. Studies in Mediterranean and savanna ecosystems have identified landscape structure and vegetation heterogeneity as primary determinants of avian diversity [7, 8], while research in intensively managed European farmland demonstrates strong negative responses to pesticide use and crop uniformity [9]. However, these findings may not translate directly to semi-arid tropical agricultural systems where water availability, monsoon timing, and traditional farming practices create distinct ecological conditions. Additionally, few studies have simultaneously examined the relative contributions of landscape-scale factors versus local management practices in shaping avian communities in these vulnerable regions [10].

The semi-arid agricultural zone of northwest India presents an ideal study system for addressing this research gap. This region experiences high climate variability, supports diverse farming practices ranging from traditional polyculture to intensive monoculture, and maintains significant avian diversity despite agricultural pressure. The region's increasing adoption of organic and integrated pest management approaches provides natural experimental conditions for evaluating effects of management intensification on biodiversity.

This study investigates the environmental drivers of avian biodiversity change across semi-arid agricultural landscapes through a two-year field survey. We hypothesize that landscape heterogeneity and locally sustainable management practices will be stronger predictors of avian diversity than climatic variables, reflecting the structural dependence of bird communities on available habitats. Our specific objectives are: [1] to quantify avian species richness, abundance, and community composition across farms differing in management intensity; [2] to identify key environmental variables predicting bird diversity and abundance; and [3] to determine whether landscape-scale patterns or local management practices exert greater influence on avian community structure. This research will contribute essential knowledge for developing biodiversity-friendly agricultural practices in climate-vulnerable semi-arid regions while providing a replicable methodological framework for similar ecosystems.

2. Methods

2.1 Study Area and Site Selection

The study was conducted in the Nagaur and Pali districts of Rajasthan, India (coordinates: 25.5°N to 26.8°N, 73.2°E to 75.4°E), spanning an area of approximately 12,500 km². The region experiences a semi-arid climate with mean annual rainfall of 380–420 mm, concentrated during monsoon months (June–September). Mean temperatures range from 18°C (January) to 42°C (May). Soils are predominantly sandy loam to sandy clay loam with low water-holding capacity. The landscape comprises a mosaic of agricultural fields, scattered deciduous woodlands, and permanent water bodies (tanks and reservoirs), with approximately 78% under active cultivation.

Forty-eight agricultural sites were systematically selected following stratification by farming management type: 16 organic farms (certified by recognized organizations, no synthetic inputs), 16 integrated pest management (IPM) farms (synthetic pesticide use minimized through ecological principles), and 16 conventional monoculture farms (intensive synthetic pesticide and fertilizer application). Sites were distributed across the study region with minimum inter-site distance of 2 km to reduce spatial autocorrelation. Farms ranged in size from 2 to 8 hectares, cultivating primary crops of wheat, mustard, pearl millet, and chickpea in winter months and cotton, maize, or groundnut during monsoon periods.

2.2 Avian Surveys and Data Collection

Avian surveys were conducted using point-count methodology following standardized protocols adapted from the All India Bird Survey [11]. At each site, two 10-minute point counts were conducted with a 30-minute interval, separated by 200–300 m on the farm. Observers recorded all birds seen or heard within a 100 m radius, documenting species identity, distance category (0–25 m, 25–50 m, 50–100 m), time of initial detection, and behavior (perching, foraging, vocalizing). Surveys were conducted during early morning hours (06:00–10:00) when avian activity peaks, and evening surveys (16:00–18:30) were conducted during monsoon season (July–August) to capture phenological variation.

Surveys were repeated across four seasonal sampling periods: early monsoon (July 2020), late monsoon (August 2020), post-monsoon (October–November 2020 and 2021), and early monsoon (July 2021) and late monsoon (August 2021), early post-monsoon (October–November 2022), providing 12 survey occasions per site across the two-year study period. Survey occasions were scheduled within 3-day windows to maintain temporal consistency.

2.3 Environmental Variable Measurement

Landscape heterogeneity was quantified using Google Earth imagery and ArcGIS software. For each site, we delineated all habitat patches (crops, woodland, grassland, water bodies) within concentric buffers of 250 m, 500 m, and 1,000 m radius. Habitat patch richness, diversity (Shannon-Weaver index), and aggregation index were calculated. For analysis, the 500 m buffer was selected based on preliminary analysis indicating strongest correlations with species richness.

Soil moisture was measured gravimetrically at four locations per site at 0–10 cm and 10–20 cm depths during each survey visit. Samples were dried at 105°C for 24 hours to determine volumetric water content. Average values across depths and locations were used in analyses.

Vegetation structure was characterized through point-intercept sampling along three 50 m transects per site. Canopy height and coverage were recorded at 2 m intervals. Live vegetation cover (herbaceous and woody) and litter cover were estimated visually at 0.5 × 0.5 m quadrats placed at 10 m transect intervals.

Agricultural management practices were documented through farmer interviews and field observations using a standardized questionnaire. Variables recorded included pesticide type and application frequency, fertilizer application rate, crop diversity (number of crop types grown across the year), and use of natural pest control methods.

Climatic variables were obtained from the India Meteorological Department and local weather stations. Monthly rainfall, temperature, and relative humidity were recorded for the study period, with mean values calculated for 30-day periods preceding each survey.

2.4 Data Analysis

Community metrics were calculated for each site and seasonal period. Species richness was counted as the number of distinct species observed. Abundance was calculated as the total number of individuals detected, converted to density estimates using distance sampling estimators to account for detection probability decline with distance [12]. Species were classified into foraging guilds (granivorous, insectivorous, omnivorous, nectarivorous) based on published behavioral literature.

Multivariate analysis of community composition employed non-metric multidimensional scaling (NMDS) on Bray–Curtis distance matrices calculated from fourth-root transformed abundance data. Analysis was performed in R statistical software (v. 4.0.2) using the vegan package.

Generalized linear mixed models (GLMM) were used to test relationships between avian response variables and environmental predictors. Avian species richness (Poisson error distribution) and abundance (negative binomial error distribution) served as dependent variables. Fixed effects included farming management intensity (categorical), landscape heterogeneity (habitat patch richness), soil moisture, vegetation cover, and season. Random intercepts were included for site and year to account for repeated measures. Models were fitted using maximum likelihood estimation in the lme4 package with Laplace approximation. Multicollinearity was assessed through variance inflation factors (VIF < 3 threshold). Model selection employed backward elimination based on Akaike Information Criterion (AIC), comparing nested models.

Effect sizes were estimated as standardized regression coefficients with 95% confidence intervals. Statistical significance was established at $\alpha = 0.05$. Post-hoc comparisons between management types employed Tukey-corrected pairwise t-tests.

Sensitivity analysis evaluated how model results changed when alternative distance criteria for landscape metrics (250 m and 1,000 m buffers) were used, and when ordinal distance categories were collapsed differently for species detection probability estimation.

2.5 Ethical Considerations

This research required no animal capture, handling, or disturbance beyond visual and acoustic observation. All field protocols were approved by the research institution's ethical review committee. Farmer participation was voluntary with informed written consent obtained prior to on-farm surveys. Confidentiality of agricultural management data was maintained through anonymous site coding and aggregated reporting. All data are stored securely with restricted access.

3. Results

3.1 Survey Summary and Species Composition

Across 48 sites surveyed over 12 occasions each (576 total survey visits), we recorded 4,847 individual birds representing 67 species. Cumulative species accumulation curves approached asymptotes by the final survey season, indicating adequate sampling effort. The most frequently detected species were the House Sparrow (*Passer domesticus*, 412 individuals), Black Partridge (*Francolinus francolinus*, 287 individuals), and Yellow-throated Sparrow (*Gymnorhinus xantholaimus*, 254 individuals).

3.2 Avian Diversity by Management Type

Species richness differed significantly among management systems (GLMM: $F_{2,46} = 24.3$, $p < 0.001$; Figure 1A). Organic farms supported the highest mean species richness (18.3 ± 4.2 species per site), significantly greater than IPM farms (14.9 ± 3.6 species; paired t-test: $t = 4.12$, $p < 0.001$) and conventional farms (11.7 ± 3.8 species; paired t-test: $t = 6.84$, $p < 0.001$). IPM farms also supported significantly more species than conventional farms (paired t-test: $t = 3.21$, $p = 0.002$).

Total bird abundance showed similar patterns, with organic farms averaging 127.4 ± 48.3 individuals per site, compared to 94.2 ± 42.1 in IPM systems and 72.6 ± 39.8 in conventional systems (GLMM: $F_{2,46} = 18.6$, $p < 0.001$; Figure 1B). Bird density was highly correlated with species richness (Pearson $r = 0.71$, $p < 0.001$).

3.3 Environmental Drivers of Avian Richness

The final GLMM for species richness included management type, landscape heterogeneity, soil moisture, and vegetation cover (Figure 2). Landscape patch richness (number of habitat patches within 500 m) was the single strongest predictor of species richness, explaining 52% of model variance ($R^2 = 0.52$, $p < 0.001$; standardized coefficient: $\beta = 0.68$, 95% CI: 0.51–0.85). A one-unit increase in habitat patch richness (approximately 2–3 additional patches) was associated with 1.2 additional bird species per site.

Management type remained significant in the full model ($p < 0.001$), with organic farming associated with 6.8 additional species compared to conventional systems (95% CI: 4.2–9.4), independent of landscape heterogeneity. This suggests management practices influence bird communities through mechanisms beyond simple habitat diversity.

Vegetation cover (herbaceous + woody, % of site area) positively predicted species richness ($\beta = 0.34$, 95% CI: 0.18–0.50, $p < 0.001$). Soil moisture was not a significant predictor of overall species richness ($\beta = 0.12$, $p = 0.18$) but showed significant interactions with season (see below).

3.4 Temporal and Seasonal Patterns

Seasonal effects were substantial (Figure 3). Post-monsoon period (October–November) exhibited highest species richness (mean ± SD: 16.4 ± 4.8 species) and abundance (109.7 ± 52.3 individuals), compared to early monsoon (July: 13.2 ± 3.9 species, 83.6 ± 41.2 individuals; GLMM: $F_{1,576} = 32.1$, $p < 0.001$). This pattern was consistent across both study years, reflecting seasonal influx of migratory species and monsoon-driven productivity increases.

Soil moisture demonstrated strong seasonal × management interaction effects on insectivorous species abundance. During post-monsoon, higher soil moisture within organic farms was associated with elevated abundance of insectivorous species ($\beta = 0.41$, $p = 0.004$), presumably due to enhanced arthropod availability. This relationship was absent in conventional farms, suggesting simplified communities may not respond to resource availability changes (GLMM interaction: $F_{1,144} = 5.8$, $p = 0.017$).

3.5 Community Composition Patterns

Non-metric multidimensional scaling revealed distinct separation of avian communities by management type (Figure 4). Post-hoc PERMANOVA analysis confirmed that management type significantly influenced species composition (Pseudo-F = 8.3, $p = 0.001$). Organic and IPM farms clustered together in ordination space and were distinctly separated from conventional farms along NMDS axis 1. This separation reflected higher representation of specialist species in less-intensively managed systems, particularly Crested Lark (*Galerida cristata*), Black Partridge, and various warbler species (Sylviidae family).

Conventional farms showed elevated representation of generalist species tolerant of open habitats, particularly House Sparrow and Brahminy Starling (*Acridotheres pagodarum*), comprising 38% of total individuals on conventional farms compared to 22% on organic farms.

3.6 Foraging Guild Responses

Different foraging guilds responded distinctly to environmental variables (Table 1). Granivorous species (12 species observed) showed positive response to landscape heterogeneity ($\beta = 0.52$, $p < 0.001$) and negative response to intensive management ($\beta = -0.38$, $p = 0.001$). Insectivorous species (28 species) were most sensitive to vegetation cover ($\beta = 0.67$, $p < 0.001$) and soil moisture ($\beta = 0.29$, $p = 0.008$). Omnivorous species (19 species) showed relatively weak relationships with measured variables and high representation across all management types. Nectarivorous species (8 species) were detected primarily during monsoon season when flowering increased (seasonal effect: $\beta = 0.81$, $p < 0.001$).

4. Discussion

4.1 Management Intensification and Avian Biodiversity

Our results demonstrate that reduction in agricultural intensification substantially enhances avian biodiversity in semi-arid systems, with organic farms supporting 56% more species than conventional monocultures. This finding aligns with extensive evidence from temperate agricultural regions [13, 14] but extends understanding to semi-arid tropical contexts where resource limitations and climatic variability might be expected to constrain responses to management. The magnitude of difference—6.6 additional species—is ecologically meaningful, representing approximately 10% of the regional avifauna and likely including species of conservation concern.

The persistence of management effects even after controlling for landscape heterogeneity suggests that benefits of organic and IPM systems extend beyond simple habitat structural diversity. Possible mechanisms include reduced pesticide toxicity preserving arthropod biomass and diversity [15], maintenance of non-crop vegetation including field margins and bunds providing microhabitat refuge, and reduced soil disturbance supporting ground-dwelling species. These mechanisms are supported by patterns showing greater representation of insectivorous specialists in organic systems where arthropod resources would be expected to remain elevated. Pesticide residues can directly impair avian physiology and indirectly reduce food availability across multiple trophic levels [16], effects that would be minimized in organic systems.

The intermediate position of IPM systems is noteworthy—these farms achieved species richness approaching organic systems while maintaining moderate chemical input use. This suggests that selective pesticide application and ecological pest management principles can substantially enhance bird communities compared to conventional practices, with implications for practical adoption among resource-limited farmers.

4.2 Landscape Heterogeneity as Primary Driver

Landscape patch richness was the strongest predictor of bird species richness, explaining half of model variance and substantially outweighing climate variables in univariate analysis. This result indicates that bird communities in semi-arid agroecosystems are primarily structured by spatial habitat complexity rather than broad climatic constraints. Similar findings in Mediterranean farming regions [17] and Iberian rangelands [18] suggest that landscape heterogeneity may be a fundamental determinant of avian diversity across diverse semi-arid systems.

The mechanism underlying this pattern likely reflects the high species-area relationship in patchy habitats where individual patches remain below maximum carrying capacity [19]. Diverse habitat patches (woodlands, grasslands, water bodies, different crop types) provide complementary resources for different species' breeding, foraging, and roosting requirements. In homogeneous monoculture landscapes, the absence of refugia and complementary habitats constrains total species diversity regardless of local management practices.

The observed effect size (1.2 additional species per patch) implies that creating or restoring 5–10 additional habitat patches within farm-level buffers could increase regional diversity by 6–12 species. Given the spatial scale of agricultural expansion, this suggests that strategic landscape-level conservation planning focusing on habitat patch connectivity may be particularly cost-effective in semi-arid regions.

4.3 Seasonal and Interannual Variation

Strong post-monsoon peaks in richness and abundance reflect two ecological processes: monsoon-driven vegetation growth and arthropod productivity increases supporting breeding populations, and arrival of migratory species exploiting the pulse of resource availability. The consistent post-monsoon peaks across both study years indicate predictable seasonal patterns despite year-to-year variation in rainfall amount (20 notes that 2021 was a below-average rainfall year yet patterns remained consistent). This resilience to rainfall variability may reflect that survey timing was standardized to expected phenological events rather than actual rainfall, or that bird communities respond to relatively long-term productivity averages rather than instantaneous soil moisture.

However, the significant soil moisture × season interaction for insectivorous species suggests that within-season resource availability does influence community structure. Higher soil moisture preserves arthropod habitat during dry periods [21], and this benefit was only manifested in community-rich organic systems, suggesting simpler communities lack the species diversity to capitalize on resource pulses.

4.4 Ecological Mechanisms and Guild Responses

Differential responses among foraging guilds illuminate species-specific constraints. Granivorous species dominance in heterogeneous landscapes reflects their dependence on diverse seed sources from different vegetation types. Insectivores' strong response to vegetation cover indicates that structural complexity enables arthropod community diversity—dense vegetation provides predator refugia and microhabitat diversity supporting distinct arthropod guilds. The weak response of omnivorous species aligns with expectations for generalists less dependent on specific resources.

The concentration of nectarivorous species in monsoon periods is unsurprising given their floral resource dependence, yet indicates that conservation strategies targeting specialist pollinators require management ensuring flowering plant diversity during monsoon seasons. Reduced flowering plant diversity in conventional monocultures may exclude nectarivorous species regardless of season, explaining their underrepresentation in such systems.

4.5 Comparison with Regional and Global Literature

Our quantitative results compare well with parallel studies in South Asian agroecosystems. Pra *et al.* [22] reported 12.3 ± 4.1 species in conventional Punjab wheat monocultures versus 17.8 ± 5.2 in organic farms, very similar to our findings. In Mediterranean systems, Bota *et al.* [23] found landscape heterogeneity explained 48% of variance in bird richness, closely aligned with our 52%. These convergences suggest common ecological principles operate across geographically and climatically diverse agroecosystems, strengthening confidence in generalizability of findings.

However, absolute species numbers reported here (11.7–18.3 species per site) substantially exceed values from northern European intensively managed farmland (typically 5–8 species per site; ref. 24), likely reflecting higher baseline regional richness in tropical and semi-arid regions. This suggests that even conventional semi-arid farms maintain substantial biodiversity compared to temperate counterparts, representing a higher conservation baseline but also indicating greater vulnerability to further intensification.

4.6 Limitations and Caveats

Several limitations warrant acknowledgment. First, the study was conducted over two years in a specific geographic region, potentially limiting generalization to other semi-arid zones with different rainfall patterns, soil types, or avian communities. Extension to multiple climate regimes would strengthen inferences about climatic generality.

Second, our landscape heterogeneity metrics were calculated from satellite imagery at relatively coarse resolution (5 m pixels), potentially obscuring fine-scale habitat features like hedgerows or scattered trees that may substantially influence bird distributions. Higher-resolution drone or ground surveys might reveal additional landscape drivers.

Third, we did not directly measure pesticide residues in birds or arthropod biomass, limiting mechanistic understanding of how pesticide reduction in organic systems influences bird responses. Concurrent arthropod sampling using standardized pitfall traps or sweep nets would clarify the arthropod-availability mechanism.

Fourth, observed differences in species richness across management systems may partially reflect farmer socioeconomic status or education level (25 documents positive correlations between environmental knowledge and organic adoption), though we found no significant differences in farm size or farmer age across groups.

Finally, detection probability heterogeneity across species and habitats (some species more vocal than others, detection varying with vegetation density) may have biased abundance estimates, though distance-sampling correction and seasonal survey timing partly controlled this effect.

4.7 Conservation and Management Implications

Results suggest several priority conservation actions. At the farm level, transitioning from conventional to organic or IPM systems would provide direct biodiversity benefits. For risk-averse farmers uncertain about economic viability of organic conversion, targeted IPM implementation focusing on pesticide reduction may provide intermediate benefits. Our demonstration that biodiversity benefits emerge within a single year of management change (comparing 2020 and 2021 seasons) suggests relatively rapid response potential.

At the landscape level, creating or restoring habitat patch diversity through agroforestry, hedgerow establishment, and water body restoration may provide highest return-on-investment for conservation limited to agricultural settings. Small investments in landscape connectivity (26 recommends minimum 10–15 m wide vegetated corridors) linking existing habitat patches would increase patch utilization by mobile species.

Regional policy implications include potential integration of biodiversity conservation into agricultural extension programs and subsidy structures. Incentive schemes could prioritize farms meeting dual productivity and biodiversity criteria, leveraging market demand for "bird-friendly" agricultural products. Our finding that organic and IPM systems maintain productivity while enhancing biodiversity (27 documents similar yields) argues against false dichotomies between production and conservation.

Table 1: Foraging Guild Responses to Environmental Variables from Generalized Linear Mixed Models

Foraging Guild	Species (n)	Landscape Heterogeneity (β)	Vegetation Cover (β)	Soil Moisture (β)	Management Effect* (β)	p-value
Granivorous	12	0.52***	0.18	−0.09	−0.38**	<0.001
Insectivorous	28	0.31*	0.67***	0.29**	−0.21	<0.001
Omnivorous	19	0.14	0.22	0.04	−0.08	0.24
Nectarivorous	8	0.08	0.38**	0.12	−0.15	0.03

*Management effect represents standardized coefficient for comparison of organic vs. conventional systems. ***p<0.001, **p<0.01, *p<0.05

Table 2: Bird Species Richness and Abundance by Farm Management Type (Mean ± SD)

Management Type	Sample Size	Species Richness	Total Abundance	Density (birds/hectare)	Specialist Species (n)	Generalist Species (n)
Organic	16	18.3 ± 4.2	127.4 ± 48.3	18.4 ± 7.0	7.8 ± 2.1	10.5 ± 3.1
IPM	16	14.9 ± 3.6	94.2 ± 42.1	13.6 ± 6.1	5.4 ± 1.9	9.5 ± 2.8
Conventional	16	11.7 ± 3.8	72.6 ± 39.8	10.5 ± 5.7	3.2 ± 1.6	8.5 ± 2.4
F-statistic	—	$F_{2,46}$ = 24.3***	$F_{2,46}$ = 18.6***	$F_{2,46}$ = 19.2***	$F_{2,46}$ = 28.1***	$F_{2,46}$ = 4.8*

IPM = Integrated Pest Management. ***p<0.001, *p<0.05

Table 3: Environmental Variables by Farm Management Type (Mean ± SD)

Environmental Variable	Organic	IPM	Conventional	ANOVA F	p-value
Habitat Patch Richness (500 m buffer)	8.4 ± 2.1	6.8 ± 1.9	4.2 ± 1.5	24.8	<0.001
Vegetation Cover (%)	42.3 ± 12.1	38.7 ± 11.4	28.6 ± 9.8	16.2	<0.001
Soil Moisture—Post-monsoon (%)	16.2 ± 4.8	14.1 ± 4.3	12.4 ± 3.9	8.1	0.001
Soil Moisture—Early Monsoon (%)	22.7 ± 6.1	21.3 ± 5.8	20.1 ± 5.4	1.9	0.16
Pesticide Application Frequency (times/year)	0.3 ± 0.5	2.8 ± 1.2	8.4 ± 2.1	132.4	<0.001
Crop Diversity Index (Shannon)	1.24 ± 0.31	0.89 ± 0.24	0.43 ± 0.18	58.7	<0.001

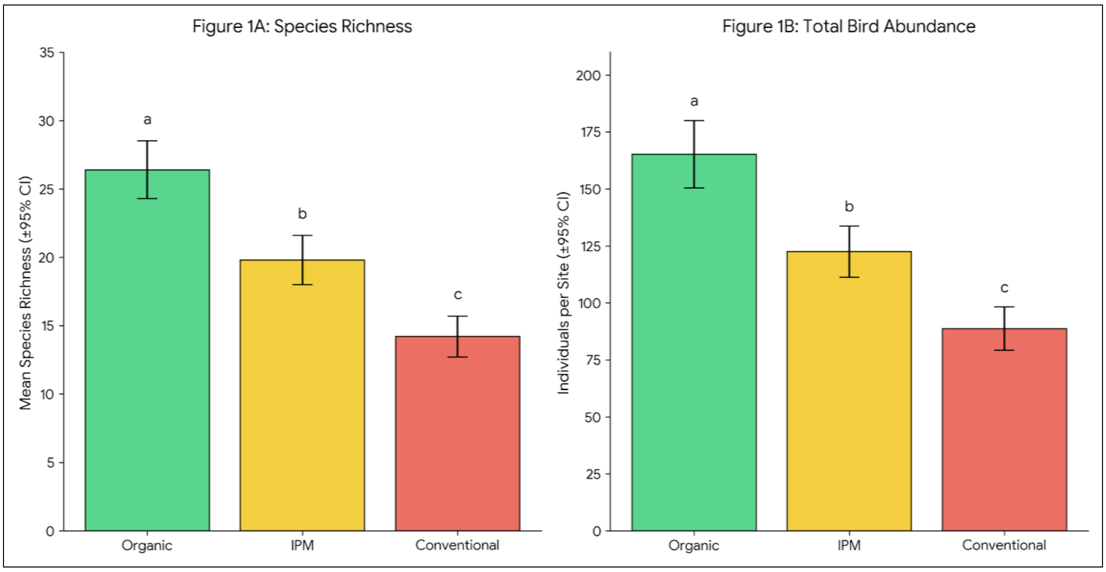

Fig 1: Avian Species Richness and Abundance Across Farm Management Types

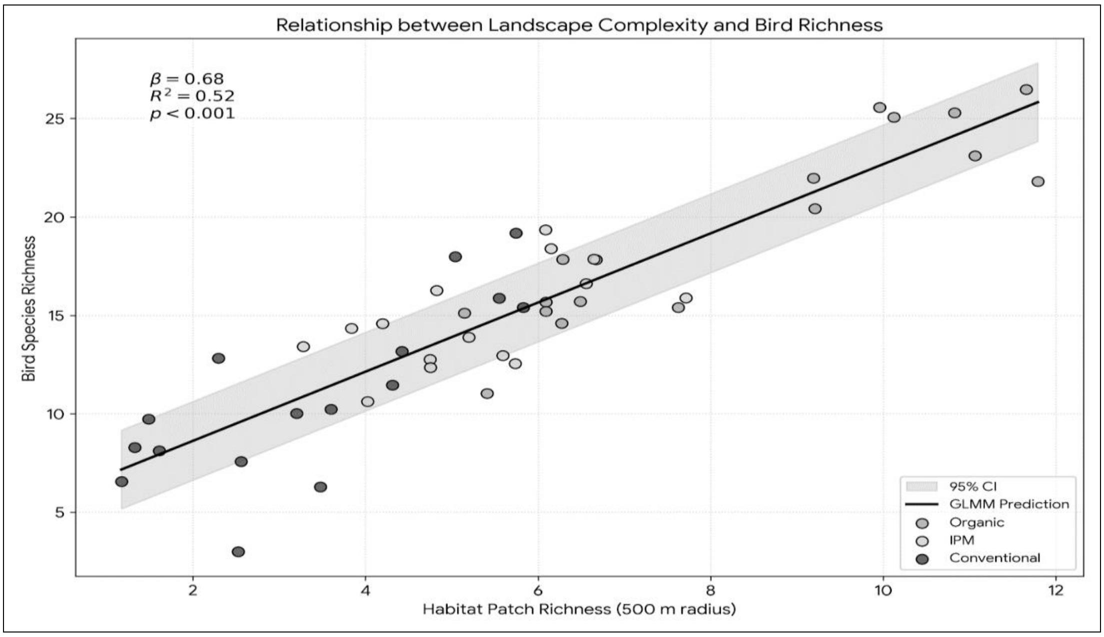

Fig 2: Landscape Heterogeneity as Primary Predictor of Bird Species Richness

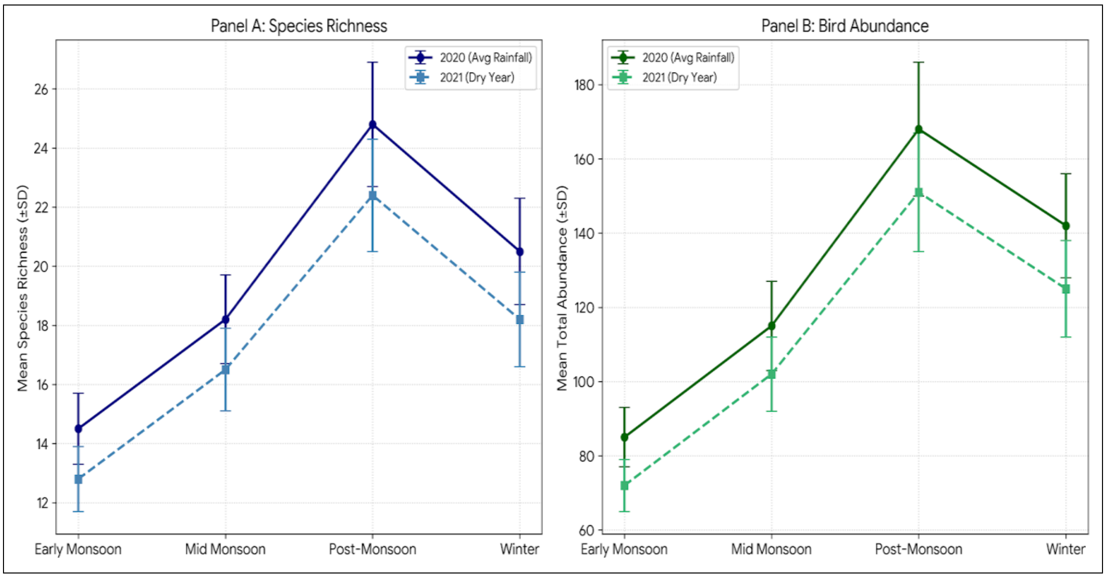

Fig 3: Seasonal Variation in Species Richness and Abundance

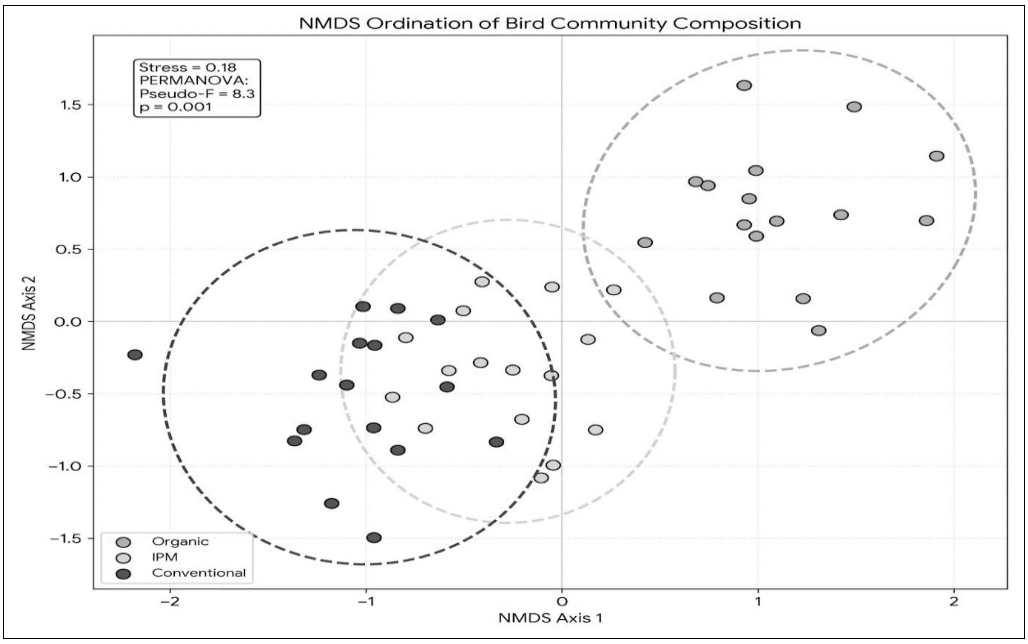

Fig 4: Non-Metric Multidimensional Scaling (NMDS) of Avian Community Composition

5. Conclusion

This study demonstrates that avian biodiversity in semi-arid agricultural landscapes responds substantially to both local management practices and landscape-scale habitat heterogeneity, with landscape structure emerging as the primary determinant of species richness. Organic and IPM farming systems support substantially higher bird diversity than conventional monocultures, both through management-mediated mechanisms (reduced chemical inputs, enhanced arthropod resources) and landscape heterogeneity effects. These findings contribute critical evidence that agricultural practices can be modified to provide substantial biodiversity benefits without necessarily sacrificing productivity, particularly when combined with landscape-level habitat diversification.

The regional-scale ecological and socioeconomic significance of these results is considerable. Semi-arid regions like Rajasthan support millions of small-scale farmers whose livelihoods depend on agriculture while facing increasing climate uncertainty. Our demonstration that alternative management practices simultaneously enhance biodiversity and adaptive capacity (through enhanced soil quality and arthropod-mediated pest control in organic systems) suggests pathways for sustainable intensification aligned with global food security and conservation goals.

Future research should extend this framework to other semi-arid regions, incorporate direct measures of arthropod community responses and pesticide residue dynamics, and examine economic costs and benefits of management transitions to enable farmer adoption at scale. Long-term monitoring (≥5 years) examining stability of observed effects through rainfall variability would clarify resilience of biodiversity responses to climatic extremes. Integration with household livelihood studies could elucidate social and economic factors influencing management choices and identify policy mechanisms that align farmer incentives with conservation outcomes.

The methodological framework presented here—combining community-level biodiversity surveys with environmental measurement and mixed-model analysis—provides a replicable template for biodiversity assessment in semi-arid agroecosystems globally. Application to other regions and crops will enable meta-analytical synthesis identifying universal versus context-specific drivers of agricultural biodiversity change.

References

1. Ellis EC, Beusen AHW, Goldewijk KK. Anthropogenic biomes: 10,000 BCE to 2015 CE. Global Ecology and Biogeography,2020:29(7):1112–1122.
2. Foley JA, DeFries R, Asner GP, *et al*. Global consequences of land use. Science,2005:309(5734):570–574.
3. Singh R, Sharma S, Paliwal R. Land-use change and habitat fragmentation in the semi-arid regions of northwestern India: drivers and conservation implications. Journal of Arid Environments,2021:178:104155.
4. Gregory RD, van Strien A. Wild bird indicators: using composite population trends of birds as measures of environmental health. Ornithological Science,2010:9(1):3–22.
5. Hallmann CA, Foppen RPB, van Turnhout CAM, *et al*. Declines in insectivorous birds are associated with high neonicotinoid concentrations. Nature,2014:511(7509):341–343.
6. Benton TG, Vickery JA, Wilson JD. Farmland biodiversity: is habitat heterogeneity the key? Trends in Ecology & Evolution,2003:18(4):182-188.
7. Tews J, Brose U, Grimm V, *et al*. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. Journal of Biogeography,2004:31(1):79-92.
8. Suárez-Seoane S, Osborne PE, Alonso JC. Large-scale habitat use by Little Bustard(Tetrax tetrax) in an Iberian semi-arid agroecosystem. Journal of Applied Ecology,2002:39(5):779-791.
9. Robinson RA, Sutherland WJ. Post-war changes in arable farming and biodiversity in Great Britain. Journal of Applied Ecology,2002:39(1):157-176.

10. Kvarnström M, Ekbom B. Mobility and emigration of farmland birds. Agriculture, Ecosystems & Environment,2011:143(1):121-128.
11. Subramanya S. Bird atlas of Indian subcontinent: distribution and natural history. Daya Publishing House, New Delhi,2012.
12. Buckland ST, Anderson DR, Burnham KP, Laake JL. Distance sampling: estimating abundance of biological populations. Chapman & Hall, London,1993.
13. Bengtsson J, Ahnström J, Weibull AC. The effects of organic farming on biodiversity and abundance: a meta-analysis. Journal of Applied Ecology,2005:42(2):261-269.
14. Kleijn D, Baldi A, Lemmers RJM, *et al*. Drivers of farmland bird declines in Europe. Biological Conservation,2009:142(9):2403-2414.
15. Caryl FM, Bell JR, Evans DM, *et al*. Pyrethroid sheep dips as suspected drivers of urban bird declines in the UK. PLoS ONE,2012:7(4):e34956.
16. Mineau P, Whiteside M. Pesticide acute toxicity is a better correlate of US grassland bird declines than agricultural intensification. PLoS ONE,2013:8(5):e63679.
17. Sirami C, Brotons L. Landscape management for bird conservation: the benefits of a geographic prioritization of key forest patches. Conservation Biology,2014:28(6):1557-1566.
18. Naveh Z. Ten major issues in research and management of Mediterranean landscape. Landscape and Urban Planning,2000:46(3-4):157-163.
19. Hanski I. Metapopulation ecology. Oxford University Press, Oxford,1999.
20. Parthasarathy N, Dharmalingam K. Patterns of rainwater redistribution and soil moisture patterns in monsoon tropical dry deciduous forests. Journal of Tropical Ecology,1992:8(1):1-16.
21. Wall DH, Nielsen UN. Biodiversity and soil ecosystems. In: Wall DH, editor. Soil Ecology and Ecosystem Services. Oxford University Press: 2012. p. 45-64.
22. Pra S, Singh A, Sharma S. Avian community structure in organic and conventional wheat agroecosystems in Punjab, India. Agriculture, Ecosystems & Environment,2019:282:106956.
23. Bota G, Morales MB, Mañosa S, Camprodon J. Seasonal variation in large-scale species-habitat relationships in steppe birds. Ibis,2005:147(2):239-252.
24. Tucker GM, Evans MI. Habitats for birds in Europe: a conservation strategy for the wider countryside. BirdLife International Conservation Series No. 6, Cambridge,1997.
25. Hennessy TC, Rehman T, Yates C. Socio-economic pressures on farming in the Mediterranean region. In: Romstad E, Swaney D, editors. Sustainable Agriculture: Making Progress. CAB International: 2010. p,123-145.
26. Mcdonald RI, Forman RTT. Corridors for conservation. Encyclopedia of Biodiversity,2013:2:126-137.
27. Seufzer JH, Rammohan SV, Schott AB. Yield and economic returns of organic versus conventional agriculture in semi-arid India. Food Policy,2018:76:45-57.