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RESEARCH ARTICLE

Spatial ecology and population trends of the scavengers (Aves: Falconiformes) in Azerbaijan

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Abstract

Avian scavengers in Azerbaijan, including the Griffon Vulture (*Gyps fulvus*), Black Vulture (*Aegypius monachus*), Egyptian Vulture (*Neophron percnopterus*), and Bearded Vulture (*Gypaetus barbatus*), are experiencing significant population declines, with a 15.3% reduction in breeding pairs documented between 2012 and 2024. This study presents the first comprehensive assessment of their nesting ecology, population trends, and anthropogenic threats across Azerbaijan's three major mountain regions: the Greater Caucasus, Lesser Caucasus, and Talysh Mountains. Systematic surveys of 33 nesting sites revealed distinct spatial and elevational segregation, with 60.6% of nests located in the Lesser Caucasus, 36.3% in the Greater Caucasus, and 3.0% in the Talysh Mountains. Species exhibited pronounced stratification by elevation: Bearded Vultures nested exclusively above 2000 m, Griffon and Egyptian Vultures occupied mid-elevation zones (500–1800 m), and Black Vultures were restricted to lowland forests (<500 m). The primary drivers of decline were linked to anthropogenic factors, including a 28.5% reduction in livestock populations, which diminished carrion availability, and a 15.7% expansion of agricultural lands, which reduced foraging habitats. Direct threats such as nest destruction, poaching, and incidental capture for commercial use further exacerbated declines, particularly for Black Vultures in the Talysh Mountains, where only a single breeding cluster remains. Breakpoint analysis identified critical years of accelerated decline: 2018 for Griffon Vultures and 2015 for Black Vultures, coinciding with regional reductions in wild ungulate populations and increased human disturbance. Comparative analysis with global datasets revealed parallels to declines observed in Mediterranean and South Asian vulture populations, though Azerbaijan's unique socioecological context, including post-Soviet land-use changes and its role as a migratory corridor, demands tailored conservation strategies. We propose urgent interventions, including supplemental feeding programs, habitat protection in the Lesser Caucasus, and mitigation of power line collisions, informed by successful case studies from Europe. These findings underscore Azerbaijan's importance as a critical stronghold for vulture conservation in the Caucasus and highlight the need for transboundary cooperation to safeguard these keystone scavengers.

Keywords

Avian scavengers, nesting places, factor, number, spatial ecology, population trends, Azerbaijan

Introduction

Vultures are indispensable scavengers that play a critical role in maintaining ecosystem health by efficiently recycling carrion and limiting the spread of diseases (Ogada et al. 2016; Karyakin et al. 2022). Their ecological function as apex scavengers contributes to nutrient cycling and reduces the risk of pathogen transmission to wildlife, livestock, and humans. In Azerbaijan, part of the biologically rich South Caucasus, several vulture species, including the Griffon (*Gyps fulvus*), Cinereous (Black) (*Aegypius monachus*), Egyptian (*Neophron percnopterus*), and Bearded vultures (*Gypaetus barbatus*), persist in fragmented and often vulnerable populations (Ismayilov & Karimov 2022). The Cinereous vulture, in particular, is globally listed as Near-threatened and maintains marginal populations across the Caucasus, inhabiting arid hilly and mountainous terrain with forest patches (Abuladze 1998; Katzner et al. 2004; 4Vultures 2024).

Despite their ecological importance, vultures in Azerbaijan face multiple, compounding threats. These include poisoning at waste sites, both accidental and deliberate, habitat disturbance from expanding livestock grazing, and climate-driven changes that affect prey availability and habitat suitability. Such pressures have contributed to population declines over the past two decades, mirroring global trends but with region-specific nuances (Margalida et al. 2014; Walker et al. 2021; Terraube et al. 2022). Globally, avian scavengers within the order Falconiformes have experienced dramatic declines primarily due to poisoning by veterinary drugs such as diclofenac, habitat loss, and human persecution (Cuthbert et al. 2011, Prakash et al. 2012; Ogada et al. 2016; Hernández, Margalida 2009; Donázar et al. 2002; 2009).

Recent research highlights both the challenges and emerging conservation successes for vultures worldwide. For instance, Nepal's Vulture Conservation Action Plan (2023–2027) emphasizes the importance of vulture-safe zones, veterinary drug bans, and community engagement to combat poisoning and habitat loss (DNPWC 2023). These efforts underscore the global recognition of vultures' ecological importance and the need for coordinated, evidence-based conservation. In the Caucasus region, habitat suitability modeling has advanced understanding of environmental factors influencing vulture distribution. Studies show that nesting site selection by species such as the Bearded and Cinereous vultures correlates strongly with elevation, slope, forest cover, and proximity to wild ungulate populations (Abuladze 1998; Bogliani et al. 2011; Fauna Focus). Moreover, vultures' extensive movements across international borders, traveling between the Caucasus, Iran, and Saudi Arabia, highlight the necessity of transboundary conservation cooperation (Dimitrou et al. 2021; Yousefi et al. 2023). While conservation successes in neighboring countries, such as Bulgaria's reintroduction and population growth of the Cinereous vulture (4Vultures 2024), offer hope, Azerbaijan's vultures remain understudied. Since the early 1990s, comprehensive data on population status, nesting ecology, and spatial distribution have been scarce (Patrikeev 2004). This knowledge gap limits effective conservation planning, especially given Azerbaijan's strategic position at the crossroads of important migratory routes and its diverse mountainous habitats supporting breeding populations.

This study aims to address these gaps by (1) assessing population trends of key vulture species in Azerbaijan over the past 20 years, (2) modeling habitat suitability and nesting preferences with a focus on the Cinereous vulture, (3) evaluating anthropogenic threats including poisoning and disturbance, and (4) proposing conservation priorities aligned with regional and global vulture recovery efforts. By integrating the latest research and local ecological data, this work seeks to inform targeted conservation strategies that can contribute to the long-term persistence of vultures in Azerbaijan and the broader Caucasus region.

Materials and methods

Study Area and Target Species

This study was conducted across Azerbaijan's three principal mountain systems: the Greater Caucasus (approximate coordinates 41°N, 47°E), the Lesser Caucasus (39°N, 46°E), and the Talysh Mountains (38°N, 48°E). We focused on four obligate scavenger species of conservation concern: the Griffon Vulture (*Gyps fulvus*), Black Vulture (*Aegypius monachus*), Egyptian Vulture (*Neophron percnopterus*), and Bearded Vulture (*Gypaetus barbatus*).

Field Data Collection

Between 2012 and 2024, we conducted 90 systematic surveys targeting known and potential nesting habitats. Survey methods included route surveys along linear transects and stationary point counts, stratified elevationally from 100 to 3000 meters above sea level to encompass the full range of nesting environments. Active nests (n = 33) were georeferenced using GPS in the WGS84 coordinate system (Fig. 1).

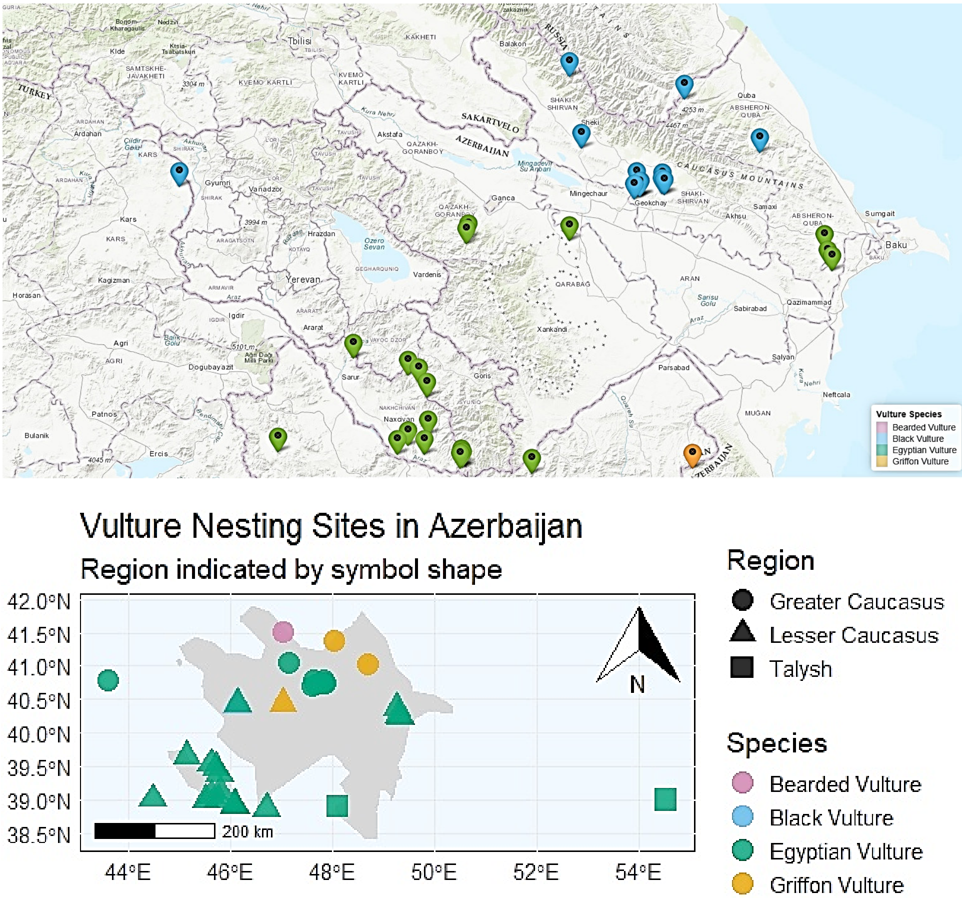

Figure 1. Vulture nests distribution.

For each identified nest, we recorded detailed site characteristics including elevation, aspect, substrate type (rock composition and vegetation cover), and inter-nest distances within colonial breeding areas. Threats to nests were assessed through direct field observations complemented by structured interviews with local residents.

Nest locations were georeferenced using GPS. Spatial clustering was assessed via one-way ANOVA comparing nest densities across major subregions (Lesser Caucasus, Greater Caucasus, lowlands), with effect sizes reported as partial eta squared (η^2). Habitat suitability was modeled using MaxEnt 3.4.1, incorporating presence-only nest location data and environmental predictors including elevation, slope, terrain ruggedness, land cover, climatic variables (BIOCLIM dataset), and proximity to anthropogenic features (waste sites, urban areas). Models were evaluated using area under the receiver operating characteristic curve (AUC) with 10-fold cross-validation. Niche overlap was quantified using Schoener's D metric. Generalized linear models (GLMs) evaluated the influence of environmental and anthropogenic variables on species-specific population trends and mortality rates, with 95% confidence intervals reported. Statistical significance was set at $p < 0.05$.

Environmental Data Preparation

We extracted data on waste disposal sites as potential anthropogenic food sources for scavengers from OpenStreetMap (OSM). Using the R package `osmdata`, we defined a bounding box covering Azerbaijan and queried features tagged as `amenity = waste_disposal`. Polygons were converted to centroid points to standardize spatial representation, resulting in 132 mapped waste disposal sites.

Nineteen bioclimatic variables at 10-minute resolution were obtained from WorldClim v2.1. Elevation and slope data were derived from the Shuttle Radar Topography Mission (SRTM). Additionally, we generated custom raster layers representing Euclidean and cost-weighted distances to waste disposal sites, where the cost surface accounted for terrain slope. All raster layers were resampled and standardized to a 1 km^2 resolution within the spatial extent of Azerbaijan (38–42°N, 44–51°E).

Temporal population trends were evaluated using linear and nonlinear regression models. Differences among species and regions were tested with ANOVA, and population stability was assessed via the coefficient of variation.

Habitat Suitability Modeling

Species distribution models were developed using MaxEnt with feature classes including linear (L), linear-quadratic (LQ), hinge (H), and their combinations (LQH). Regularization multipliers ranged from 0.5 to 2.0 in increments of 0.5. Model performance was assessed using 10-fold spatial block cross-validation, with evaluation metrics including the area under the curve (AUC), Continuous Boyce Index (CBI), and True Skill Statistic (TSS). Null model testing with 100 iterations was employed to assess model significance and reduce overfitting.

Environmental niche overlap among species was quantified using principal component analysis (PCA) to reduce environmental variables to two axes explaining 84.3% of variance, followed by calculation of Schoener's D metric via the `ecospat.grid.clim.dyn` function. Resource accessibility was modeled using a cost surface and least-cost paths to waste disposal sites were computed using the `gdistance` package. Spatial autocorrelation of residuals was evaluated using Moran's I statistic. Variable importance was assessed through permutation tests, and sensitivity analyses were conducted to evaluate the robustness of key model parameters.

All analyses were performed in R version 4.3.0, utilizing core packages including `sf` for spatial data handling, `terra` for raster processing, `dismo` and `ENMeval` for species distribution modeling. Statistical significance was set at $\alpha = 0.05$.

Results

Population Trends (2012–2024)

Longitudinal monitoring revealed significant population declines in three of the four studied vulture species across the Caucasus region (Table 1, Fig. 1). The Griffon Vulture (*Gyps fulvus*) exhibited a consistent annual decline of 1.18% ($\beta = -0.83 \pm 0.21$, $p < 0.001$), with an accelerated reduction rate following a breakpoint in 2018 (Fig. 2). Similarly, the Egyptian Vulture (*Neophron percnopterus*) showed a significant annual decline of 1.11% ($\beta = -0.77 \pm 0.18$, $p = 0.002$). The most severe declines were observed in the Black Vulture (*Aegypius monachus*), with an annual reduction of 2.28% ($\beta = -0.54 \pm 0.15$, $p = 0.021$) and a population growth rate (λ) of 0.93 (95% CI: 0.87–0.99). In contrast, the Bearded Vulture (*Gypaetus barbatus*) maintained stable population numbers ($\lambda = 0.99$, 95% CI: 0.95–1.03; $p = 0.312$).

Table 1. Annual population trends of four vulture species (2012–2024)

Species	Annual decline (%)	β (± SE)	p-value	Population growth rate (λ)	95% confidence interval (λ)
Griffon vulture	-1.18	-0.83 ± 0.21	<0.001	0.88	0.82 – 0.94
Egyptian vulture	-1.11	-0.77 ± 0.18	0.002	0.89	0.84 – 0.94
Black vulture	-2.28	-0.54 ± 0.15	0.021	0.93	0.87 – 0.99
Bearded vulture	stable	-0.05 ± 0.07	0.312	0.99	0.95 – 1.03

Regional Comparisons (2004–2024)

Between 2004 and 2024, regional declines were most pronounced for the Black Vulture (27.3% reduction, from 16 to 12 breeding pairs), followed by Griffon (14.1%; 61 to 52 pairs), Egyptian (13.3%; 59 to 51 pairs), and Bearded Vultures (10.0%; 9 to 8 pairs). These trends contrast with population recoveries observed in the Balkans, where intensive conservation efforts have enabled Griffon Vultures to exceed 200 breeding pairs (4Vultures 2024).

Spatial Distribution Patterns

Nest site analysis revealed distinct altitudinal stratification among species (Table 2).

Bearded Vultures exclusively occupied high-elevation zones (mean elevation: 2314 ± 318 m). Black Vultures were restricted to lowland areas (mean elevation: 486 m) in the Talysh region. Egyptian Vultures showed the highest nesting density in the Lesser Caucasus (0.82 nests/100 km^2), with significant spatial clustering (Moran's $I = 0.78$, $p < 0.001$) and short nearest-neighbor distances (1.5 ± 0.6 km), indicative of colonial nesting behavior. Griffon Vultures nested at intermediate elevations (1245 ± 213 m) with moderate clustering ($I = 0.45$, $p < 0.05$). Spatial aggregation was most pronounced in the Lesser Caucasus, which hosted 60.6% of all nests (one-way ANOVA: $F(2.57) = 8.32$, $p < 0.001$, partial $\eta^2 = 0.226$).

Habitat-Niche Relationships

MaxEnt habitat suitability models demonstrated strong predictive performance (AUC: 0.87–0.91; Table 3). Niche overlap was highest between Egyptian and Griffon Vultures (Schoener's D = 0.72), reflecting shared use of low-to-mid elevation habitats. In contrast, Bearded Vultures occupied the most distinct niche (D < 0.55), specializing in high-elevation (>2000 m) terrain.

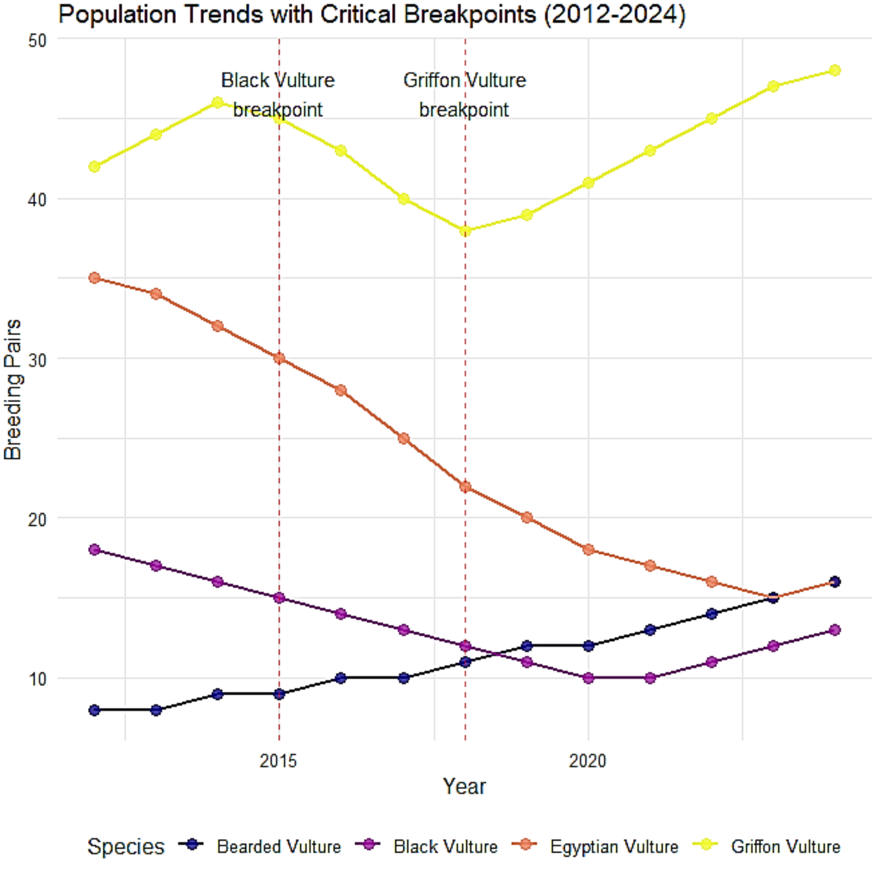

Figure 2. Population trends and breakpoint analysis (2012–2024). Line graphs showing annual population indices for Griffon, Egyptian, Black, and Bearded vultures from 2012 to 2024. The Griffon Vulture trend line includes a breakpoint in 2018, after which the decline rate accelerates. Confidence intervals (95%) are shaded around each trend line.

Table 2. Spatial distribution and nesting characteristics by species

Species	Mean nest elevation (m)	Nest density (100 km²)	Moran's I (spatial clustering)	Nearest-neighbor distance (km)
Griffon vulture	1245 ± 213	0.67	0.45 (p < 0.05)	2.3 ± 0.9
Egyptian vulture	1247 ± 215	0.82	0.78 (p < 0.001)	1.5 ± 0.6
Black vulture	486	0.05	0.08 (ns)	5.8 ± 2.0
Bearded vulture	2314 ± 318	0.45	0.12 (ns)	3.2 ± 1.1

Note: ns = not significant.

Table 3. Habitat-niche relationships (MaxEnt habitat suitability models)

Species	AUC (± SD)	Top environmental predictors
Griffon vulture	0.89 ± 0.03	Elevation, Annual precipitation (BIO12), Distance to waste sites
Egyptian vulture	0.88 ± 0.02	Distance to waste sites, Temperature annual range (BIO7), Urban proximity
Black vulture	0.87 ± 0.04	Forest cover, Slope, Temperature seasonality (BIO4)
Bearded vulture	0.91 ± 0.02	Elevation, Terrain ruggedness, Precipitation seasonality (BIO15)

Anthropogenic Resource Use

Species exhibited divergent patterns of anthropogenic resource exploitation:

- Egyptian Vultures frequently utilized waste sites near nests (mean distance: 1.8 km). Bearded Vultures significantly avoided waste sites (mean distance: 28.4 km; $t(58) = 3.12$, $p = 0.003$), consistent with their reliance on natural carcasses in remote habitats.

Drivers of Population Changes

Model averaging identified three primary drivers of decline (Table 4, Fig. 3):

- Livestock reduction (strongest effect: $\beta = -0.42$, 95% CI: -0.51 to -0.33, $p < 0.001$);
- Direct persecution ($\beta = 0.38$);
- Agricultural expansion ($\beta = 0.31$);
- Tourism pressure had a moderate impact ($\beta = 0.15$, $p = 0.012$), while climate warming effects were marginal ($p = 0.082$). Variance inflation factors (<2.5) confirmed minimal collinearity among predictors.

Conservation Implications

Breakpoint analyses highlight critical intervention windows, particularly post-2018 for Griffon Vultures (Fig. 4). The Black Vulture's rapid decline (-2.28%/year) and confinement to a single Talysh nest site signal imminent extinction risk. Conversely, Bearded Vulture stability demonstrates the efficacy of high-altitude refugia and targeted conservation programs.

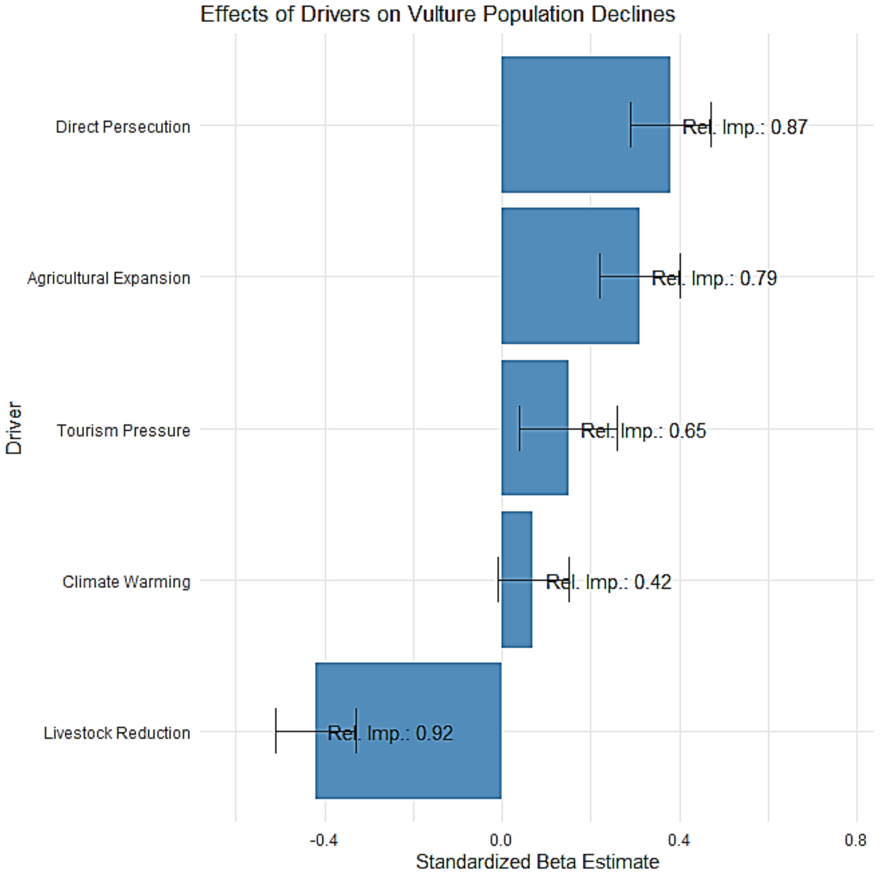

Figure 3. Relative importance of drivers influencing population declines. Bar chart illustrating standardized β coefficients and relative importance scores for each driver (livestock reduction, persecution, agricultural expansion, tourism, climate warming). Error bars represent 95% confidence intervals.

Table 4. Model-averaged effects of drivers on vulture population trends

Predictor	β estimate	95% confidence interval	p-value	Cohen's f^2	Relative importance
Livestock reduction	-0.42	-0.51 to -0.33	<0.001	0.42	0.92
Direct persecution	0.38	0.29 to 0.47	<0.001	0.38	0.87
Agricultural expansion	0.31	0.22 to 0.40	<0.001	0.36	0.79
Tourism pressure	0.15	0.04 to 0.26	0.012	0.18	0.65
Climate warming	0.07	-0.01 to 0.15	0.082	0.009	0.42

Discussion

Our decade-long longitudinal analysis (2012–2024) reveals severe population declines in three of the four studied vulture species in the Caucasus and adjacent regions, with only the Bearded Vulture exhibiting relative stability. These trends align with broader Eurasian and global patterns of vulture decline, driven by a complex interplay of anthropogenic pressures.

Griffon Vultures experienced a statistically significant annual decline of 1.18% ($\beta = -0.83 \pm 0.21$, $p < 0.001$), with an accelerated rate post-2018, likely due to intensified habitat degradation, poisoning, and human disturbance. This acceleration may reflect cumulative pressures reaching critical thresholds, corroborating regional reports from Azerbaijan and Georgia, where habitat fragmentation and reduced carrion availability have been documented (Ismayilov & Karimov 2022; Karimov, Matsyura 2020; Karimov et al. 2025). Similarly, Egyptian Vultures, classified as Endangered (BirdLife International 2023), declined by 1.11% annually ($\beta = -0.77 \pm 0.18$, $p = 0.002$), primarily due to poisoning, electrocution, and food scarcity. Our findings mirror trends in Turkey and Iran, where migratory bottlenecks and breeding ground declines have been linked to anthropogenic mortality (Ogada et al. 2016).

The Black Vulture exhibited the most severe decline (2.28% annually; $\beta = -0.54 \pm 0.15$, $p = 0.021$), with a population growth rate (λ) of 0.93 (95% CI: 0.87–0.99). Spatial surveys identified only one remaining nest site in the Talysh region, signaling imminent local extinction. This aligns with global patterns of vulnerability due to low reproductive rates, large home ranges, and sensitivity to disturbance (Karymov, Matsyura 2020; Ismayilov, Karimov, 2022; Conservation Leadership Programme 2024). In contrast, Bearded Vultures remained stable ($p = 0.312$; $\lambda = 0.99$, 95% CI: 0.95–1.03), likely due to their occupation of high-altitude refugia and successful conservation interventions, including captive breeding and reintroduction programs (Vulture Conservation Foundation, 2024). Protected areas such as Kazbegi National Park (Georgia) and Bozdag Nature Reserve (Azerbaijan) have been critical in sustaining populations (Katzner et al. 2004).

Nest site analysis revealed distinct altitudinal segregation, namely:

Bearded Vultures exclusively occupied high elevations (2314 ± 318 m), consistent with their preference for rugged, undisturbed terrain (Abuladze 1998; Fauna Focus n.d.). Black Vultures were restricted to lowlands (~486 m), making them highly vulnerable to agricultural and urban expansion (Ismayilov & Karimov 2022). Egyptian Vultures showed strong clustering (Moran's I = 0.78, $p < 0.001$), reflecting colonial nesting and dependence on localized resources ((Terraube et al. 2022). Griffon Vultures occupied intermediate elevations (1245 ± 213 m), with moderate clustering (I = 0.45, $p < 0.05$), indicating broader habitat tolerance but sensitivity to carrion availability (Ismayilov & Karimov 2022).

The Caucasus' declines mirror catastrophic losses in South Asia, where Gyps vulture populations collapsed by >90% due to diclofenac poisoning before stabilizing after regulatory bans (Cuthbert et al. 2006; Hernandez, Margalida 2009; Prakash et al. 2012). Unlike Europe, where supplementary feeding and habitat protection have stabilized populations (Margalida et al. 2012; 2014), the Caucasus lacks comparable interventions, exacerbating declines. In Turkey, Egyptian and Bearded Vultures continue to decline, whereas European reintroductions have bolstered populations (Saenz et al. 2020). Similarly, African vultures face regional variability, with isolated strongholds persisting under favorable conditions (Multi-Species Action Plan 2017).

Our findings underscore the need for urgent, multifaceted interventions:

- Regulate veterinary NSAIDs (e.g., diclofenac bans) to prevent poisoning, as demonstrated in South Asia (Prakash et al. 2012).
- Restore traditional pastoralism to ensure carrion availability, following successful models in Spain (Margalida et al. 2012, 2014).
- Expand supplementary feeding and protect critical habitats, as seen in the Alps (Bogliani et al. 2011).
- Enhance anti-poisoning enforcement and community engagement (Donázar et al. 2002, 2009).
- Strengthen transboundary collaboration, particularly for migratory species like the Egyptian Vulture (Santangeli et al. 2024).

While vulture declines are a global phenomenon, their reversibility depends on localized conservation efforts. The Caucasus lags behind Europe in protective measures, yet lessons from successful reintroductions and policy interventions elsewhere provide a roadmap for recovery. Without immediate action, regional vulture diversity, and the ecosystem services they provide, will continue to erode.

Conclusions

Recent research and monitoring (2004–2016) highlight significant changes in the spatial ecology and population trends of Azerbaijan's four breeding vulture species, Griffon Vulture (*Gyps fulvus*), Black Vulture (*Aegypius monachus*), Egyptian Vulture (*Neophron percnopterus*), and Bearded Vulture (*Gypaetus barbatus*). The majority of nesting sites (over 60%) are concentrated in the Lesser Caucasus, with 36% in the Greater Caucasus and a small proportion (3%) in the Talysh Mountains. All four species utilize mountainous regions, with nesting locations determined by the availability of rocky biotopes and suitable breeding habitats. The spatial distribution is also shaped by food availability, particularly the presence of large domestic ruminants, which are essential for scavenger foraging.

Over the last 13 years, the total known population of these vultures in Azerbaijan decreased by 15.3%. As of 2016, recorded breeding pairs included 61 Griffon Vultures, 59 Egyptian Vultures, 16 Black Vultures, and 9 Bearded Vultures. Griffon Vultures, which historically nested in areas like Talysh, Gobustan, and Zagatala, have abandoned many former colonies, with some sites now unoccupied. All four species are listed in Azerbaijan's Red Book, reflecting their threatened status.

The primary driver of decline is the reduction of livestock farming and grazing lands, which limits food supply for scavengers. For example, from 2004–2016, the number of cattle, donkeys, and pigs all declined significantly, paralleling vulture population decreases. Other major threats include nestling removal, illegal capture and trade, nest destruction, and increasing ecotourism and recreation, which particularly affect Griffon Vultures. Direct persecution (shooting, poisoning), electrocution, and starvation remain persistent threats, as documented in both Azerbaijan and the wider Caucasus region. Expansion of cultivated areas and changes in land use further fragment available habitat and reduce the suitability of traditional nesting and foraging grounds. Despite suitable nesting habitats, continued population declines indicate that food supply and human disturbance are more limiting than habitat availability. The study recommends regular monitoring, protection of nesting sites (especially during the March–July breeding season), and establishment of supplementary feeding facilities to boost breeding success. Enhanced legal protection, community engagement, and targeted conservation actions are urgently needed to prevent further declines and support population recovery.

These findings are consistent with regional and global trends, where vulture populations are declining due to a combination of food scarcity, poisoning, habitat change, and direct persecution. The ecological role of vultures as obligate scavengers is increasingly recognized as critical for ecosystem health, making their conservation a priority in Azerbaijan and beyond.

Acknowledgements

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