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Anuran richness and abundance along an elevational gradient in Chebera Churchura National Park, southwestern Ethiopia

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Abstract

Elevational gradients are fundamental drivers of biodiversity, yet their influence on anuran communities in many of Ethiopia's protected areas remains poorly understood. This study investigated the altitudinal distribution, species richness, and abundance of anurans in Chebera Churchura National Park (CCNP), southwestern Ethiopia. Using a combination of standardised visual encounter surveys (VES) and pitfall traps, we sampled along an elevational gradient from 865 m to 2400 m, which corresponds to three major transitions in temperature, vegetation structure, and moisture regimes. Surveys were conducted during both wet and dry seasons. We recorded 2,175 individuals representing 16 species from eight families. Species richness and abundance followed unimodal (hump-shaped) distributions, peaking at mid-elevations (~1,200 m). Quadratic regression confirmed that intermediate altitudes provide an ecological optimum for anuran communities, while diversity declines towards lower and higher elevations. These results highlight the importance of mid-altitude habitats as local centres of high anuran diversity within CCNP. However, the occurrence of elevation-restricted species and the observed variation in diversity along the altitudinal gradient indicate that different elevational zones support distinct anuran communities. This underscores the importance of conserving habitats across the full altitudinal range of CCNP, particularly mid-elevation areas with high diversity as well as habitats supporting range-restricted species. Protection of indigenous forests and permanent aquatic habitats, including rivers, streams, and wetlands, is therefore critical for sustaining anuran diversity within the park.

Keywords: Amphibians, community ecology, hump-shaped distribution, altitudinal zonation, Ethiopia, ecological optimum, habitat conservation, range-restricted species, VES, pitfall traps

Introduction

Amphibians, as ectothermic vertebrates with highly permeable skin and complex life cycles closely linked to moisture availability, are particularly sensitive to environmental gradients such as altitude (Duellman & Trueb 1994; Wells 2007). Changes in elevation influence temperature, humidity, primary productivity, and breeding-site availability, all of which affect not only amphibian species richness but also abundance and community dominance patterns. Consequently, altitudinal gradients provide a powerful framework for examining variation in amphibian community structure (Rahbek 1995; McCain 2007).

Numerous studies on amphibians have demonstrated that elevational gradients can produce diverse richness patterns, including monotonic and unimodal (hump-shaped) distributions, depending on the interaction between climatic factors, habitat heterogeneity, and species' ecological tolerances (Naniwadekar & Vasudevan 2007; Wang et al. 2020).

Globally, amphibian species richness along elevational gradients exhibits diverse patterns, including monotonic declines, increases, and hump-shaped distributions, reflecting the combined influence of climatic gradients, environmental heterogeneity, and spatial constraints (McCain 2005; Naniwadekar & Vasudevan 2007; Wang et al. 2020).

In particular, variation in temperature and moisture availability has been shown to strongly influence amphibian richness along elevational gradients, with soil moisture and thermal conditions often acting as key predictors of species distribution patterns (Naniwadekar & Vasudevan, 2007). Similar patterns have been observed for amphibian abundance, where mid-elevational zones often support higher population densities due to optimal thermal conditions, greater prey availability, and reduced environmental stress compared to lowland or high-altitude extremes (Pineda & Halffter 2004; Wells 2007).

Ethiopia is characterised by dramatic topographic variation encompassing savannahs, lowland forests, and extensive highland systems, and it harbours a rich and highly endemic anuran fauna. More than 80 anuran species have been recorded in the country, approximately half of which are endemic, with endemism particularly concentrated in the highlands (Largen 2001; Largen & Spawls 2010). Despite growing recognition of the ecological importance of altitudinal gradients for understanding anuran diversity and population dynamics, many areas in Ethiopia, protected and unprotected, remain poorly studied (Gower et al. 2013; Menegon et al. 2014).

In particular, there is a lack of small-scale data linking anuran richness, abundance, and species composition to elevational variation within individual protected areas. Although anuran species richness and abundance are often reported to follow unimodal (hump-shaped) elevational patterns, the elevation at which peaks occur, the strength of the pattern, and the dominant species driving these trends vary considerably among regions depending on local climate, habitat structure, and disturbance regimes (Rahbek 1995; McCain & Grytnes 2010; Hu et al. 2011).

Elevation acts as a proxy for a range of climatic and ecological gradients, including temperature, precipitation, microclimate, habitat conditions, and resource availability, which in turn directly influence the distribution, abundance, and diversity of species (Vasconcelos et al. 2010; Moura et al. 2016).

Chebera Churchura National Park (CCNP), located in southwestern Ethiopia, represents an important and understudied landscape due to its wide elevational range and diverse habitats, which likely support distinct anuran communities, coupled with minimal prior research on its herpetofauna. Investigating anuran diversity along elevational gradients in CCNP is therefore essential for establishing baseline ecological data, highlighting elevational zones that may warrant targeted conservation attention, and assessing the extent to which general elevational diversity patterns apply within this protected area.

Therefore, this study investigated elevational patterns of anuran species richness and abundance across an elevational gradient in Chebera Churchura National Park. Specifically, the study evaluated whether anuran diversity and abundance exhibit a hump-shaped distribution along the elevational gradient as reported from other geographic areas (Rahbek 1995; McCain 2007).

Materials and methods

Study area

We conducted the study in Chebera Churchura National Park (CCNP), located approximately 580 km southwest of Addis Ababa. The park lies within the Dawro Zone (Churchura) and the Konta Special District (Chebera), between 6°39′–7°09′N latitude and 36°27′–36°57′E longitude. Covering an area of about 1,250 km², CCNP is bordered by the Konta Special District to the north, the Omo River to the south, Dawro Zone to the east and southeast, and the Agare high mountains and the Omo River to the west (Abebe et al. 2010; Debela et al. 2017).

The park is characterised by predominantly undulating to rolling plains with few flat areas, interspersed with rivers, perennial streams, valleys, gorges, and several small crater lakes (Tadesse et al. 2014). The elevational range spans from approximately 560 m to over 2400 m above sea level, contributing to substantial habitat heterogeneity and microclimatic variation (Debela et al. 2017; Figure 1, Table 1).

The climate of CCNP is characterised by a unimodal rainfall pattern, with the rainy season extending from March to October and mean annual rainfall ranging between approximately 1,200 mm and 2,200 mm. Mean annual temperatures are generally moderate, ranging from about 15°C to 25°C (Debela *et al.* 2017; Tadesse *et al.* 2014).

The park is traversed by rivers, which provide critical breeding habitats for anurans and other aquatic organisms (Tadesse *et al.* 2014). Owing to its ecological importance and relatively intact habitats, CCNP has considerable potential for the conservation of Ethiopia's lesser-studied vertebrate groups, including anurans. However, the area is increasingly affected by human pressures such as livestock grazing, settlement expansion, and agricultural encroachment (Abebe *et al*. 2010; Tesfaye *et al.* 2013).

Land-use practices in and around CCNP are dominated by traditional shifting cultivation and livestock farming. Major crops cultivated include enset (*Ensete ventricosum*), sorghum, and maize, while coffee production and honey harvesting represent important sources of household income for local communities (Abebe *et al*. 2010; Tesfaye *et al.* 2013).

Sampling design

We randomly selected five sampling sites within the park to cover the full elevational gradient, with inter-site distances ranging from 5 to 15 km (Adnew *et al*. 2026). We established four transects at each of the five sites, resulting in a total of 20 transects across the study area. Transects followed a rectangular layout of 600 m, consisting of a 200 m north–south extension and a 100 m east–west extension from a randomly selected starting point, following the design of Rödel and Ernst (2004). Transects within each site were spaced at least 150–200 m apart to avoid overlap of survey areas.

Our sampling sites and transects spanned elevations from 865 m to 2,400 m. For each of the 20 transects, a single geographic coordinate and elevation point was recorded at the starting location using a Garmin Vista GPS. Elevation measurements of the GPS were cross-checked in the field using an altimeter, which was calibrated daily against topographic maps to ensure accuracy.

In CCNP, the habitat types change with altitude from lowland woodland to submontane and Afromontane forest systems. We therefore followed Friis *et al*. (2010) and grouped the 20 transects into three elevation zones (low: 560–1000 m, mid: 1001–1800 m, and high: 1801–2400 m).

Sampling was carried out during both the wet (June–October) and dry (November–April) seasons between June 2022 and April 2024, to account for seasonal variation in anuran activity, as species are typically more active and detectable during the wet season due to breeding and favourable moisture conditions, whereas activity is reduced during the dry season.

Each transect was surveyed for three hours per session, over six days, separately during the wet and dry seasons. A team of three observers sampled two transects per day, walking at a constant speed. Surveys were conducted in the morning from 06:00 to 09:00 and at night from 06:00 to 09:00, with head torches used to maximise species detection and abundance.

Data collection

Anuran surveys incorporated multiple techniques, including visual encounter surveys (VES), acoustic encounter surveys (AES), opportunistic observations, and trapping methods (drift fences with pitfall traps), following standard protocols (Heyer *et al.* 1994).

However, to ensure a standardised sampling effort across all elevational gradients, only data obtained from individuals encountered during formal VES and AES along fixed transects were included in the quantitative analyses of species richness and abundance. Each transect was sampled with equal frequency and duration at every site.

Opportunistic sightings and trapping data were utilised solely to compile a comprehensive species inventory for the region (Adnew *et al*. 2026) and were excluded from site-to-site statistical comparisons to maintain methodological consistency.

Species identification was performed in the field whenever possible. Specimens that could not be identified on site were collected as voucher specimens for further examination. Molecular species identification was subsequently conducted in the laboratory (Adnew *et al*., 2026).

Environmental variables

Temperature and precipitation are generally recognised as drivers of anuran abundance and species richness (Buckley & Jetz 2007; McCain 2007), and these climatic factors are usually strongly correlated with altitude (Körner 2007; Lomolino 2001). Since we do not have small-scale climate data for our study sites, we used altitude recorded with a GPS device as a proxy for these climatic variables.

In addtion we classified the area of our study sites according to the intensity of anthropogenic disturbance. Disturbance intensity was quantified at each transect using a four-level scale (0–3) adapted from Khatiwada *et al*. (2019), incorporating indicators such as livestock grazing, deforestation, and agricultural expansion:

- 0 (Undisturbed): No visible signs of human impact.
- 1 (Low): No grazing and distant from permanent human settlements.
- 2 (Moderate): Evidence of grazing and proximity to agricultural areas, but distant from settlements.
- 3 (High): Intensive grazing and situated near human settlements.

Data analyses

Species richness and abundance were analysed using Generalized Linear Models (GLMs) as response variables. Species richness was modelled with a Poisson error distribution, whereas abundance was analysed using a negative binomial distribution to account for overdispersion. In both models, altitude and disturbance level were included as predictor variables to evaluate their effects on the anuran community. All statistical analyses were performed in R (R Core Team 2024).

Elevational pattern analysis

To examine potential non-linear elevational patterns, quadratic regression models were used to test for unimodal (hump-shaped) relationships between altitude and species richness or abundance. The significance of the quadratic term ($Altitude^2$) was used to confirm the presence of a non-linear trend along the gradient.

Results

Accumulation curve

Species accumulation curves approached an asymptote across sampling sites, indicating that the survey effort was sufficient to capture all anuran species present along the elevational gradient in CCNP (Figure 2).

Model selection and predictors of diversity

Generalized Linear Models (GLMs) were employed to identify the environmental predictors for species richness and abundance. To address the high multicollinearity identified during preliminary assessments (VIF > 5.0), altitude and anthropogenic disturbance were selected as the final independent variables, while temperature and precipitation were excluded from the formal models.

Initial linear regressions indicated that altitude did not have a significant linear relationship with species richness ($p = 0.440$). However, because anuran distributions often follow non-linear patterns, we tested a quadratic (polynomial) model for altitude. The inclusion of the quadratic term ($Altitude^2$) significantly improved the model fit (Table 2), confirming a non-linear, mid-elevational relationship for both richness and abundance.

The quadratic GLM results indicated that altitude had a significant unimodal effect on both species richness ($z = -2.41$, $p < 0.05$) and abundance ($z = -3.12$, $p < 0.01$). This confirms the hump-shaped distribution observed in the raw data, where diversity peaks at mid-elevations.

Although precipitation yielded a marginally lower AIC in linear comparisons, altitude was retained as the primary predictor because it serves as a robust integrative proxy for the complex climatic and environmental gradients within Chebera Churchura National Park (see Supplementary Material for the full model code).

Elevational patterns of species richness and abundance

As expected, species richness and abundance of arurans exhibited a distinct unimodal (hump-shaped) pattern across the elevational gradient. Quadratic regression analyses confirmed a significant mid-elevation peak for both metrics, whereas linear models failed to capture the non-linear nature of the distribution.

Aruran species richness increased from lower altitudes, reaching a maximum of 10 species at approximately 1,200 m, followed by a steady decline toward higher altitudes (Figure 3a: Table S1). The relationship is described by the following quadratic model:

$$S = -4.21\ X\ 10^{-6}A^2 + 0.0127A - 5691.54$$

(Where S is species richness and A is altitude in meters).

Total abundance followed a congruent trend, peaking at 657 individuals at approximately 1,200 m (Figure 3b). The quadratic model accounted for the observed variation more effectively than linear alternatives, as expressed by the equation:

$$N = -1.82 \times\ 10^{-4}A^2 + 0.562A - 295.03$$

(Where N is the total number of individuals).

These results suggest that mid-elevations provide the optimal environmental conditions and habitat complexity required to support the highest diversity and density of aruran communities within the CCNP.

Comparison of species richness and abundance among elevation zones

Fourteen of the 16 detected anuran species exhibited their highest abundances at mid-elevations (Table S2). The total abundance of anurans at mid-elevations (1001-1800m) was 1,456 individuals, which was higher than at higher (466 individuals) and lower elevations (253 individuals) (Table 3). The community was dominated by four species: *Ptychadena anchietae* (n = 408), *Conraua beccarii* (n = 301), *Hoplobatrachus occipitalis* (n = 252), and *Xenopus clivii* (n = 248), which together accounted for approximately 56% of the total recorded abundance.

Mid-elevations were characterised by higher species evenness and the coexistence of multiple dominant taxa, whereas low and high elevations were dominated by a smaller subset of specialised or generalist species

Elevational patterns in anuran diversity

Kruskal-Wallis H tests revealed significant differences across the three elevational zones for both species richness (X^2 = 8.84, df = 2, p = 0.012) and total abundance (X^2= 7.92, df = 2, p = 0.019) (Table 4). Post-hoc pairwise comparisons using Dunn's test with a Bonferroni adjustment indicated that the mid-elevation zone (1001–1800m) was significantly more diverse than the low-elevation zone ($p < 0.05$). While the mid-elevation zone also showed higher mean richness than the high-elevation zone, the difference between low and high zones was not statistically significant ($p > 0.05$), supporting the observation of a mid-elevational peak in anuran community structure.

Environmental drivers of richness and abundance

The anuran community in CCNP is structured by altitude and anthropogenic disturbance (Table 5). Both species richness and abundance exhibited a significant quadratic relationship with altitude ($p < 0.05$), confirming a unimodal (hump-shaped) distribution that peaks at mid-elevations.

Anthropogenic disturbance exerted a consistent, negative effect on the anuran community. For every unit increase in disturbance grade, species richness declined by an estimate of -0.34 ($p < 0.001$) and abundance by -0.68 ($p < 0.001$). The low Variance Inflation Factor for disturbance (VIF = 1.8) confirms that habitat degradation limits anuran diversity independently of elevation, justifying our selection of predictors and the exclusion of redundant environmental variables.

Discussion

Elevational distribution and species richness

Our results demonstrate a rapid accumulation of species, with richness reaching a near-asymptotic level at approximately 1200m. When considering 1200m as the mid-elevation zone for this study, the pattern conforms to a mid-elevational peak (Figure 2), a phenomenon widely documented in amphibian communities globally, including studies from tropical Asia and montane ecosystems that report similar mid-elevation peaks or complex richness patterns driven by overlapping species ranges and environmental gradients (McCain & Grytnes 2010; Naniwadekar & Vasudevan 2007; Wang *et al*. 2020).

The fact that 94% of all recorded species were present by this mid-elevation point suggests that the transition from lowland forest to mid-altitude habitats (around 1200m) provides a "climate-habitat optimum." At this altitude, the combination of high humidity, moderate temperatures, and diverse breeding sites likely supports a wider array of both generalist and specialist species. Conversely, the sharp decline in the rate of new species additions above 1200m indicates that the higher elevations (up to 2400m) may present physiological barriers—such as lower nocturnal temperatures or reduced hydroperiods—that limit the community to a smaller subset of high-altitude specialists.

Elevational patterns and environmental determinants

The unimodal (hump-shaped) distribution of aruran species richness and abundance in Chebera Churchura National Park (CCNP) indicates that intermediate elevations (~1200 m) provide the most favourable ecological conditions. Our quadratic regression models statistically confirmed this relationship, demonstrating that diversity does not follow a simple linear response to the elevational gradient.

At lower elevations, aruran communities are likely constrained by a combination of higher environmental stress and intensive anthropogenic disturbance (Levels 2–3), which often limit habitat suitability. Conversely, high-altitude zones—while generally less disturbed—may experience physiological constraints related to cooler thermal profiles and potentially reduced habitat heterogeneity. These mid-elevation peaks align with patterns documented in other tropical montane ecosystems (McCain, 2007), highlighting the global prevalence of the "mid-domain effect" or optimal climate-energy availability at intermediate scales. For example, studies on Mount Emei in China also reported a clear hump-shaped pattern in amphibian richness, with peak diversity at intermediate elevations, attributed to optimal climatic conditions and habitat complexity (Wang *et al.* 2020). These findings underscore the high conservation value of mid-elevation habitats in CCNP and suggest that biodiversity management should prioritise these zones to sustain regional anuran populations. Similarly, empirical studies have shown that abiotic factors such as soil moisture and temperature can explain a substantial proportion of variation in amphibian species richness along elevational gradients, highlighting the importance of microclimatic conditions in shaping community structure (Naniwadekar & Vasudevan 2007).

Elevational zonation and regional importance

The 16 anuran species recorded across the elevational range of 865–2400 m represent approximately 20% of Ethiopia's known anuran fauna. This significant richness within a localised area highlights the role of Chebera Churchura National Park (CCNP) as a critical biodiversity corridor in southwestern Ethiopia (Mengistu 2012; NABU 2020; Kassie *et al.*2023).

The mid-elevation zone (1001–1800 m) emerged as the primary diversity hotspot, supporting 14 species and nearly 70% of all recorded individuals. In contrast, low elevations (560–1000 m) supported fewer taxa, while high elevations (1801–2400 m) showed a significant reduction in abundance despite maintaining moderate richness. This unimodal distribution aligns with documented trends in other tropical montane regions, including the Eastern Afromontane, the Tropical Andes, and Southeast Asian mountains (Rahbek 1995; McCain 2007; Tang *et al.*2024).

Maintaining robust ecological connectivity across this entire elevational gradient is essential to allow species to navigate environmental fluctuations and ensure the long-term persistence of these aruran communities. Elevation itself acts primarily as a surrogate for multiple interacting environmental variables, including temperature, humidity, and habitat structure, which collectively determine amphibian distribution and diversity patterns across mountain systems (Wang *et al.* 2020)

Species-specific distribution and ecological plasticity

Anuran species in CCNP exhibited distinct distribution patterns, ranging from broadly distributed generalists to narrow-range specialists. Generalists such as *Ptychadena anchietae*, *Ptychadena nilotica*, and *Sclerophrys regularis* occurred across multiple elevation zones, demonstrating high ecological plasticity. Among these, *P. anchietae* exhibited the widest range (865–1850 m) and the highest overall abundance, suggesting a high tolerance for varying environmental conditions.

In contrast, several taxa showed restricted ranges indicative of environmental filtering. Species such as *Ptychadena baroensis* and *Sclerophrys gutturalis* were confined to low-to-mid elevations, where they appear more tolerant of the higher anthropogenic disturbance levels (Levels 2–3) recorded in these zones.

Conversely, high-elevation zones supported species adapted to cooler, more humid Afromontane conditions, such as *Ptychadena neumanni* and *Hyperolius viridiflavus*. Aquatic and semi-aquatic taxa, including *Conraua beccarii*, *Hoplobatrachus occipitalis*, and *Amietia nutti*, were primarily associated with mid-to-high elevations. This distribution likely tracks the consistent availability of permanent water bodies and specialised riparian habitats found within the submontane and montane systems of the park.

The role of altitude as an integrative proxy

A key finding of this study is the role of altitude as a composite proxy for tightly coupled environmental gradients. Although temperature and precipitation were excluded from the final regression models to prevent model instability—given their high multicollinearity with elevation—preliminary Pearson correlations and CCA ordination confirmed their defining role in shaping community structure. Altitude effectively summarises the ecological transition from warmer, drier, and more anthropogenically disturbed (Levels 2–3) lowland sites to cooler, more humid, and less disturbed highland habitats.

Treating altitude as an integrative variable allowed for robust statistical inference while respecting the inherent structure of montane environments. In these systems, physiological drivers such as oxygen partial pressure, UV radiation, and ambient humidity change in tandem with elevation. The observed mid-elevation peak likely reflects a "climatic optimum"—a zone where thermal and hydric conditions overlap with high habitat heterogeneity to support the greatest diversity of anuran species.

Influence of disturbance and community structure

Canonical Correspondence Analysis (CCA) demonstrated that anuran communities in CCNP are structured by the interplay of the elevational gradient and anthropogenic pressure. CCA Axis 1 represented the primary environmental transition, while Axis 2 captured variation in community structure, separating the highly productive mid-elevation sites from the disturbed lowlands and the less abundant high-altitude areas.

The consistent negative influence of anthropogenic disturbance across the entire gradient is a significant conservation concern. Lowland transects clustered near disturbance vectors, which correlated with reduced abundance and increased desiccation risk. Notably, our GLM results confirmed that habitat degradation (Levels 2–3) exerts a significant, independent negative pressure on both species richness and abundance, regardless of altitude. This suggests that while altitude and its associated climate parameters dictate the potential distribution of arurans, human activities—such as intensive grazing and deforestation—are the primary limiting factors for their actual persistence within the park.

Conclusion

Our results demonstrate that anuran species richness and abundance follow a significant unimodal (hump-shaped) elevational pattern, peaking at intermediate elevations (~1200 m). The absence of a simple linear relationship suggests that altitude does not act as a singular driver but rather serves as a robust integrative proxy for a complex suite of interacting climatic and environmental factors that shape community assembly.

Multivariate analyses, including CCA and GLM, identified the elevational gradient and anthropogenic disturbance as the primary forces structuring these anuran communities. Mid-elevation zones appear to represent an ecological "optimum," likely characterised by favourable moisture availability and high habitat heterogeneity.

In contrast, diversity at lower elevations is increasingly constrained by higher environmental stress and intensive human encroachment (Disturbance Levels 2–3), while higher elevations are limited by cooler Afromontane conditions and reduced environmental suitability for many generalist taxa. The presence of elevation-restricted specialists further highlights the sensitivity of these communities to fine-scale environmental variation.

From a conservation perspective, the mid-elevation habitats of CCNP function as critical biodiversity hotspots. Effective management must prioritise the protection of key breeding habitats, such as wetlands and riparian zones, within this elevational band. Simultaneously, minimising habitat degradation and maintaining landscape connectivity across the entire gradient is essential to ensure species can navigate environmental shifts. These findings provide a vital ecological baseline for long-term monitoring and support evidence-based strategies to safeguard Ethiopia’s unique and climatically sensitive aruran diversity.

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Manuscript layout (Figure page)

Figure 1. Geographic location of Chebera Churchura National Park in Ethiopia and distribution of the four major habitat types sampled. Triangles indicate the locations of the five study sites (details on altitude and habitat disturbance are provided in Table 1).

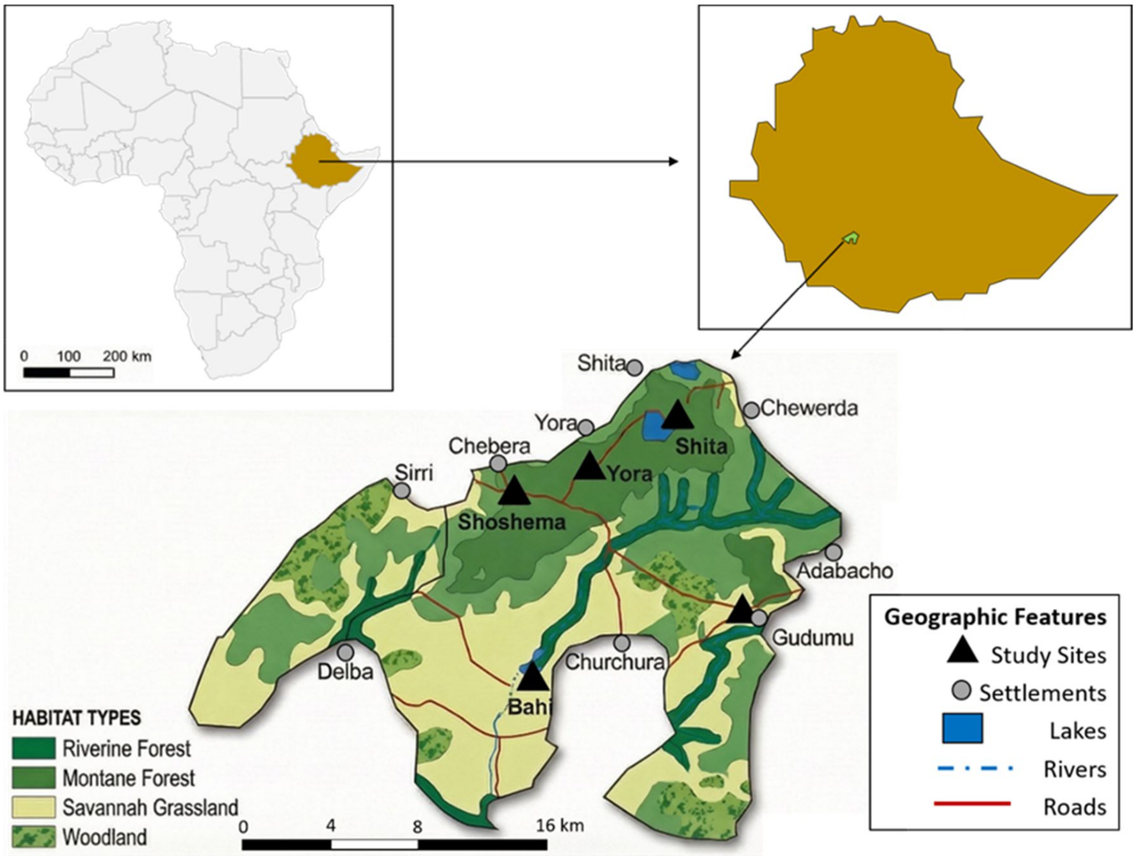


Figure 2. Cumulative species richness and abundance of anurans along an elevational gradient in Chebera Churchura National Park, southwestern Ethiopia.

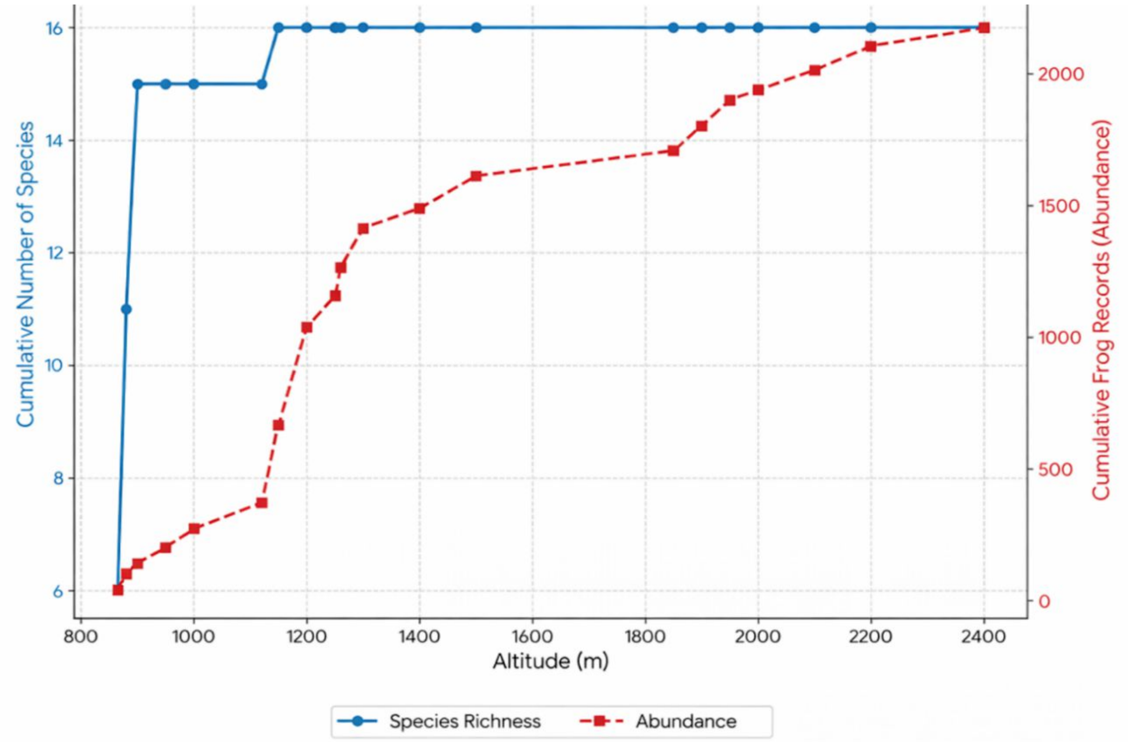
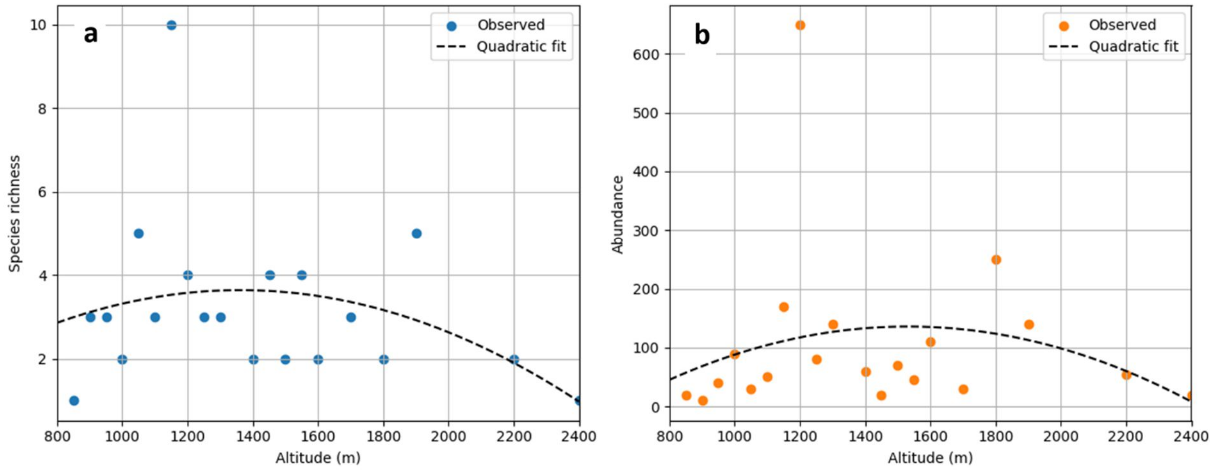


Figure 3. Quadratic relationships between altitude and aruran species richness (a) and abundance (b) in Chebera Churchura National Park, southwestern Ethiopia. Dash lines represent predicted values from quadratic regression models; points represent observed data. Both species richness and abundance show a clear mid-elevation peak, supporting the hypothesis of a hump-shaped distribution along the elevational gradient.



Manuscript layout (Table page)

Table 1. Values of environmental factors for the 20 transects (altitude; disturbance grade: 0 = no sign of disturbance; 1 = no grazing and distant from settlements; 2 = moderate grazing, near agriculture, but distant from human settlements; 3 = intensive grazing near human settlements).

Site	Transect No.	altitude (m)	elevation zone	disturbance grade
Shoshuma	1	1200	mid	3
Shoshuma	2	1850	high	2
Shoshuma	3	1500	mid	0
Shoshuma	4	1250	mid	0
Yora	5	1300	mid	3
Yora	6	1120	mid	1
Yora	7	1400	mid	2
Yora	8	1150	mid	3
Yora	9	1000	low	2
Shita	10	950	low	2
Shita	11	2200	mid	0
Shita	12	1260	mid	0
Shita	13	2100	high	1
Shita	14	2400	high	1
Gudumu	15	880	low	1
Gudumu	16	1900	high	1
Gudumu	17	2000	high	3
Gudumu	18	865	low	0
Gudumu	19	1950	high	3
Bahi	20	900	high	3

Table 2. Comparison of generalized linear models (GLM) for anuran species richness and abundance along environmental gradients in Chebera Churchura National Park.

Response Variable	Predictor	AIC	Coefficient	z-value	p-value
Richness	Altitude (Linear)	88.77	-0.0001	-0.772	0.440
	Altitude² (Quadratic)	82.15	-0.00002	-2.41	0.016*
Abundance	Altitude (Linear)	1018.17	-0.0002	-4.72	< 0.001*
	Altitude² (Quadratic)	945.30	-0.00004	-3.12	0.002*

Note: AIC = Akaike Information Criterion (lower values indicate better model fit). Bold values indicate the best-fit model for each response variable. Asterisks (*) indicate statistical significance at $p < 0.05$.

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Table 3. Anuran species' elevational ranges and abundances across three elevation zones in Chebera Churchura National Park.

Species	Range (m)	Low	Mid	High	sum
Ptychadena anchietae	865–1850	64	211	133	408
Ptychadena baroensis	875–1000	56	0	0	56
Ptychadena nilotica	880–1900	40	80	10	130
Ptychadena neumanni	1900	0	0	12	12
Sclerophrys regularis	900–1900	35	72	20	127
Sclerophrys gutturalis	1000–1200	30	85	0	115
Sclerophrys garmani	950–1200	28	58	0	86
Sclerophrys xeros	1100–1250	0	53	0	53
Xenopus clivii	1500–1900	0	90	158	248
Amietia nutti	1120–1900	0	100	29	129
Phrynobatrachus natalensis	1200–2200	0	90	20	110
Phrynobatrachus sp. 1	1200–1900	0	4	10	14
Conraua beccarii	1150–1900	0	280	21	301
Hoplobatrachus occipitalis	1150–2200	0	220	32	252
Hyperolius viridiflavus	1300–2400	0	61	20	81
Kassina senegalensis	1260–1400	0	51	0	51
Sum	865-2400	253	1456	466	2175

Table 4. Results of Kruskal-Wallis H tests and post-hoc comparisons for anuran diversity across elevational zones.

Parameter	Low (560–1000m)	Mid (1001–1800m)	High (1801–2400m)	Kruskal-Wallis ($\chi 2$)	p-value
Species Richness	2.00 ± 1.10^{a}	$4.00 \pm 2{,}45^{b}$	2.75 ± 1.71^{ab}	8.84	0.012
Abundance	42.17 ± 29.58^{a}	132.0 ± 175.7^{b}	116.5 ± 109.8^{ab}	7.92	0.019

Note: Data are presented as Mean ± SD. Different superscript letters (^a, ^b) indicate significant pairwise differences ($p < 0.05$) based on Dunn's post-hoc tests with Bonferroni correction.

Table 5. Summary of final Generalized Linear Model (GLM) results for the effects of altitude and anthropogenic disturbance on aruran communities.

Response Variable	Predictor	Estimate	Std. Error	z	p
Richness (S)	(Intercept)	1.842	0.215	8.56	< 0.001
	Altitude² (Quadratic)	-0.00002	0.000	-2.41	0.016
	Disturbance	-0.341	0.102	-3.34	< 0.001
Abundance	(Intercept)	5.124	0.412	12.43	< 0.001
	Altitude² (Quadratic)	-0.00004	0.000	-3.12	0.002
	Disturbance	-0.682	0.154	-4.43	< 0.001

Note: Richness modelled via Poisson GLM; Abundance via Negative Binomial GLM. Temperature and precipitation were excluded due to multicollinearity (VIF > 5.0). Altitude² represents the unimodal (hump-shaped) trend.

Supplementary material

Table S1. Altitudinal distribution, species richness, and abundance of amphibians in CCNP

Table S2. Anuran species recorded within altitudinal ranges.

Statistical model code