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Environmental influences on the abundance and distribution of gastropods in Edu Local Government Area, North Central Nigeria

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Abstract

Schistosomiasis transmission in endemic regions involves various bulinid species of freshwater gastropods, whose distribution and abundance are influenced by environmental factors. While much research has focused on disease prevalence, this study examines the ecological factors shaping gastropod species abundance and distribution, with a focus on bulinid species in Edu LGA. Snail abundance was collected fortnightly over twelve months, covering both rainy and dry seasons, using a standardized snail scoop net. Environmental variables were measured with standard meters. Data analysis was performed with Canoco 5.15 using GLM and RDA, and a significant level of $p < 0.05$ was considered. A total of 4,760 snails belonging to eight species were recovered. Dominant bulinid species included *Bulinus jousseaumei, Bulinus globosus, and Biomphalaria pfeifferi*, each exhibiting distinct seasonal abundance and distribution patterns that were significantly associated with environmental variables. *Bulinus jousseaumei* demonstrated a significant negative relationship with water depth. *Bulinus globosus* responded significantly to water temperature, alkalinity, and water depth. *Biomphalaria pfeifferi* showed significant responses to water temperature, conductivity ($R^2 = 11.1\%$, $p = 0.00425$). The findings revealed that water temperature, alkalinity, and conductivity were key predictors of gastropod species abundance and distribution. Understanding these relationships is crucial for ecological management and controlling snail intermediate hosts in freshwater ecosystems.

1. Introduction

Schistosomiasis is a neglected tropical disease caused by parasitic blood flukes of the genus *Schistosoma* and it remains one of the most widespread parasitic infections globally [1]. An estimated 800 million people are at risk of the disease, with 90% of cases occurring in sub-Saharan Africa [2]. The disease is transmitted when individuals are exposed to freshwater sources containing cercariae, the infective larval

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stage of the parasite [3]. These larvae are released by infected freshwater snails, which serve as intermediate hosts. These freshwater snails are part of a broader group of molluscs known as gastropods.

Gastropods are a diverse class of molluscs typically characterized by a single, coiled shell and a muscular foot used for locomotion [4]. While they serve important ecological functions in aquatic environments, certain species also play a critical role in the life cycle and transmission of schistosomiasis and other parasitic diseases.

In Africa, snails of the genera, *Bulinus* and *Biomphalaria* serve as intermediate hosts for urogenital and intestinal schistosomiasis, respectively [1,5]. In different areas, the transmission of schistosomiasis sustained by wide spread of *Bulinus* snails across freshwater ecosystems, especially in rural communities where human-water contact is frequent [6,7].

The distribution and abundance of bulinid snails are strongly influenced by environmental conditions and human activities [6]. Over 37 bulinid species are known to transmit schistosomiasis across Africa, the Middle East, and other endemic regions [8,9]. These snails inhabit freshwater bodies where they feed on plant matter and anchor to substrata to avoid displacement by water currents [10]. Their development and survival are modulated by environmental variables such as rainfall, temperature, water chemistry, water flow, and vegetation [11–14]. Other factors like conductivity, dissolved oxygen, calcium, magnesium, and pH have also been reported to influence bulinid seasonal abundance [15,16]. Despite their epidemiological significance, research on the ecological dynamics of bulinid snails in Nigeria is increasing but remains insufficient. While numerous studies in Nigeria have focused on the diagnosis, prevalence, and intensity of schistosomiasis [17–20], relatively few have investigated the physicochemical and ecological factors influencing the abundance and distribution of bulinid species in Kwara State [21]. Furthermore, critical Local Government Areas (LGAs) like Edu are often overlooked despite being predisposed to factors like shortage of clean water. This led us to investigate Edu LGA in Kwara State for schistosomiasis transmitting snails focusing on bulinid species.

Edu LGA, located in North Central Nigeria, is characterized by diverse aquatic ecosystems, including rivers, streams, ponds, and irrigation canals, which may provide suitable habitats for these snails. Environmental changes, such as agricultural runoff, nutrient enrichment, climate variability, and land-use modification can alter these habitats, potentially increasing the risk of schistosomiasis transmission [22,23]. In areas where agriculture is the main livelihood, such as Edu LGA, these changes are particularly pronounced.

Although schistosomiasis is endemic in many parts of Nigeria, including the Middle Belt region, ecological research on the distribution and habitat preferences of bulinid snails and other freshwater gastropods remains limited. Fine-scale ecological mapping of snail habitats in high-risk but understudied areas such as Edu LGA is scarce [15]. Few studies have explicitly integrated seasonal physicochemical variations such as nutrient loading, ionic composition, and hydrological dynamics into analyses of snail abundance and community structure [24, 25]. Furthermore, while intermediate host species like *B. globosus* and *Biomphalaria pfeifferi* have been relatively

well studied [16,25,26], there is a notable paucity of data on the ecological responses of non-intermediate host species, despite their potential role in local freshwater biodiversity and ecosystem functioning. In addition, much of the existing work has relied on simple correlation analyses, which, although informative, may overlook the complex, multivariate interactions that shape gastropod distribution and abundance [25]. This methodological gap limits the predictive value of prior studies for designing targeted, evidence-based snail control interventions.

This study was designed to investigate the interactions between abundance of gastropod species and environmental predictors. The primary objective of the study was to assess how the physicochemical characteristics of aquatic habitats influenced the distribution and seasonal dynamics of snail populations. It was hypothesized that (i) variation in snail abundance was significantly influenced by fluctuations in physicochemical water quality parameters, and (ii) seasonal changes impacted the ecological suitability of habitats for bulinid species. Understanding these ecological drivers is essential for informing schistosomiasis control strategies and mitigating the public health impact of the disease.

2. Materials and methods

2.1. Study area

Edu LGA is one of the sixteen LGAs in the State, with Lafiagi serving as its administrative center. It is situated between longitudes 4°54'15"E and 5°31'00"E of the Greenwich Meridian and latitudes 8°35'38"N and 9°15'00"N of the Equator. Covering a total area of 2,542 km², the LGA had a recorded population of 201,469 based on the 2006 national census. This study was carried out in six (Basita S1, Basita S2, Tada S1, Tada S2, Pataringi S1, and Pataringi S2) purposively selected locations within Edu LGA of Kwara State, Nigeria.

2.2. Snail sampling

Snails were collected fortnightly from the six sample stations (a distinct location along a natural water body where ecological sampling was conducted) in Edu LGA. Each sampling station was defined as a segment of a freshwater body, approximately 10 meters in length and 3 meters in width, depending on site accessibility and the size of the water body. Snail sampling was carried out within these demarcated areas using a standard scoop net along the shoreline and in shallow zones where snail activity was most likely to occur. The six stations comprised active human-water contact points along the river and sampling was conducted once a month during the rainy season (April to November) and the dry season (December to March). Snail sampling was done by the same collector for consistency, using a snail scoop net (30 cm by 30 cm side, 400-μm mesh size). The duration for sample collection was 20 minutes [27]. Snails recovered were washed and gently placed in a plastic container with a perforated lid for aeration.

2.3. Identification of the snails/Infection in snail species

The snails collected were taken to the laboratory where they were sorted into taxonomic groups using taxonomic keys [28]. All bulinid species were exposed to direct sunlight to induce cercarial shedding (the process by which an infected snail intermediate host releases larval stage of a parasite (e.g., cercariae) into the environment). The light-induced cercarial shedding method was employed, following the procedure described by Salawu and Odaibo [26], to confirm the presence or absence of cercariae in the collected snails. Each snail was placed individually in a wide-mouthed glass specimen bottle containing 30 mL of dechlorinated water. The snails were exposed to indirect natural sunlight between 9:00 a.m. and 1:00 p.m. each day to stimulate cercarial emergence.

After exposure, 15 mL of water from each bottle was transferred to a Petri dish and examined under a stereomicroscope for the presence of cercariae, following the method described by Uthpala et al. [29].

This procedure was repeated daily under the same conditions for seven days, after which snails were considered negative for infection. The water in each container was replaced daily to prevent the accumulation of toxic waste products from

the snails. None of the bulinid species shed cercariae using this method; however, molecular analysis revealed that some of the bullinids were infected [30].

2.4. Physicochemical analysis

Physicochemical parameters of the water bodies were assessed both *in situ* and in the laboratory. These included water temperature (Twat, °C), dissolved oxygen (mg/L), pH, carbon dioxide (CO_2, mg/L), air temperature (Tair, °C), and conductivity (μS/cm), all measured using digital meters (Hach Company, Loveland, USA). Water speed (m/s) was determined by releasing a harmless dye (methylene blue) and recording the time it took to travel a known distance along the sampling transect. Water depth (cm) was measured using a calibrated pole, while transparency (cm) was determined using a Secchi disk. For laboratory analysis, 2-liter water samples were collected in clean, labelled plastic bottles (kept in the dark) at each sampling station and transported on ice to the laboratory. Calcium (mg/L), magnesium (mg/L), nitrate (mg/L), phosphorus (mg/L), and alkalinity (Alk, mg/L $CaCO_3$) were analyzed following standard procedures recommended by the American Public Health Association (APHA) [31] at the Environmental and Water Quality Laboratory of Mainstream Energy Nigeria Limited and the Department of Industrial Chemistry, Kwara State University, Malete.

2.5. Data analysis

Each freshwater snail species recovered was a unique code for easy identification and efficient data entry in the software. These included *Melanoides tuberculata* (M.t.), *Gabbiela tchadiensis* (G.t.), and *Lymnaea natalensis* (L.n.). Others were *Bulinus jousseaumei* (B.j.), *Bulinus globosus* (B.g.), and *Ameriana carinata* (A.c.). *Biomphalaria pfeifferi* was coded as Biom.p., while *Indoplanorbis exustus*, abbreviated as I.e.

To minimize multicollinearity among environmental predictors, pairwise correlation analyses were first conducted. Variables showing strong correlations (Pearson's $r > 0.7$) or high multicollinearity (Variance Inflation Factor, VIF > 10) were excluded. Principal Component Analysis (PCA) was then applied to visualize the structure of the environmental dataset, reduce dimensionality, and derive composite axes for subsequent analyses. Redundancy analysis (RDA) was used to examine the relationships between environmental predictors and species abundance. A hierarchical permutation scheme with 999 restricted permutations tested the significance of both simple and conditional terms. Results were expressed as the percentage of explained variance, pseudo-F values, and associated p-values (unadjusted and adjusted), with significance determined at $p < 0.05$. The analyses were performed using Canoco 5.15 [32]. Furthermore, Time was treated as a continuous numeric variable in partial redundancy analysis (partial-RDA), with sampling station included as a covariate. Species-level responses to Time were modeled using generalized linear models (GLMs), also controlling for station. These models did not account for temporal autocorrelation; therefore, temporal patterns were interpreted with appropriate caution. To complement the multivariate ordination analyses, univariate GLMs were used to generate Species Response Curves (SRCs), modeling each species' abundance separately against each environmental variable. A quasi-Poisson distribution with a log-link function was applied to account for over-dispersion and ensure non-negative predictions. This approach also provided reliable F-statistics for significance testing. For each species–predictor pair, we reported the dispersion parameter (ϕ), pseudo-R^2 values and the shape of each response shape (linear, unimodal, or cubic). All variables were standardized before analysis to ensure comparability.

3. Results

3.1. Abundance of gastropods in aquatic habitats within Edu LGA

Across Edu LGA, *Melanoides tuberculata* was the most widespread and abundant snail species, particularly in Pataringi and Tada stations. *Lymnaea natalensis* was the second most abundant species, dominating at Pataringi Station 2. Snail

intermediate hosts (*Bulinus globosus* and *Biomphalaria pfeifferi*) were less abundant but widely distributed, with *B. globosus* most common at Tada Station 2. Non-vector species such as *Indoplanorbis exustus* were localized, occuring mainly in Basita and Tada (S1 Table).

3.2. Seasonal variations in physicochemical parameters across Edu LGA

The physicochemical properties across stations in Edu LGA revealed distinct seasonal variations, with parameters fluctuating in response to the rainy (May to September) and dry (October to April) seasons. Air and water temperatures peaked during the dry season, with the highest air temperatures recorded at Tada Station 1 in February and Pataringi Station 1 in March. Water temperatures followed a similar trend, with peaks observed in February, particularly at Tada Station 2 and Basita Station 1. Water depth and transparency were highest during the rainy season, with Basita Station 1 recording a depth of 45.7 cm in August, while transparency peaked at Basita Station 2 in November. Dissolved oxygen concentrations were highest at Basita Station 1 and Tada Station 2 in May but lowest at Pataringi Station 2 in October and November. pH values varied across stations, with a slightly basic values at Basita Station 1 during the dry season and a lower values at Pataringi Station 2 during the rainy season (S2 Table).

Seasonal changes also influenced concentrations of key chemical parameters. Calcium levels were highest at Pataringi Station 2 in April, while magnesium peaked at Pataringi Station 1 in June. Nitrate concentrations were highest in the rainy season, with Basita Station 1 recording a peak of 8.6 mg/L in September. Phosphate levels showed slight increases in October at Basita Station 1, while conductivity reached its maximum in December at Tada Station 2. Alkalinity was highest at Basita Station 1 in September (S2 Table).

3.3. RDA between the species abundance and the environmental variables

Speed was identified as the most influential predictor in both simple and conditional effects analyses, explaining 25.3% of the variance in species composition. This effect was highly significant ($p < 0.001$) for the simple term effect. Nitrate (N) also contributed significantly, explaining 20.5% of the variance in the simple term analysis ($p = 0.003$). However, its conditional effect, after accounting for other predictors, dropped to 4.11% and was not significant ($p = 0.062$).

Depth explained 19.6% of the variance, with a pseudo-F value of 17.1 in the simple term analysis ($p < 0.001$). However, its conditional effect dropped substantially, explaining only 0.3% of the variance, which was not significant ($p = 0.867$); therefore, it was not considered further. This suggests that the effect of depth on species composition is largely interdependent with other environmental variables. Conductivity (Cond) was also a a significant predictor in the simple term analysis, explaining 16.7% of the variance ($p = 0.005$). However, its conditional effect was minimal, explaining only 0.88% of the variance.

Carbon dioxide (CO_2) also showed significant simple term effects, explaining 16.5% of the variance ($p = 0.002$). However, tts conditional effect was reduced, accounting for for only 1.53% of the variance. Magnesium (Mg) explained 11.8% of the variance, with marginal significance ($p = 0.027$) in the simple term analysis. its conditional term effect was considerably lower, explaining 1.12% of the variance which was not significant ($p = 0.343$). For Calcium (Ca), the simple term effect explained 11.6% of the variance, but this was not significant ($p = 0.058$). The conditional term effect was 10.09%, also not significant ($p = 0.15$). Dissolved Oxygen (DO) showed similar results, with a simple term effect of 10.3% variance and a conditional effect of 3.83% (Table 1).

In the Redundancy Analysis (RDA) of species composition constrained by all environmental variables (excluding temporal factors), the Monte Carlo permutation test (999 permutations) within a hierarchical design yielded a pseudo-F value of 4.9 ($p = 0.005$). The adjusted explained variation (R^2-adj) was 43.63%. The corresponding RDA with all predictors is illustrated in Fig 1. In the RDA diagram, all predictors were included. Both simple effects (the unique contribution of each explanatory variable when considered individually) and their conditional effects (the contribution of each predictor after

Table 1. Tested effects (simple and conditional) of the environmental predictors on the species composition by an RDA.

Simple term effects					Conditional term effects				
Variables	**Explains %**	**pseudo-F**	**P**	**P(adj)**	**Variables**	**Explains %**	**pseudo-F**	**P**	**P(adj)**
Speed	25.3	23.7	0.001	0.007	Speed	25.3	23.7	0.001	0.014
N	20.5	18.1	0.003	0.011	Ca	10.09	10.8	0.15	0.42
Depth	19.6	17.1	0.001	0.007	DO	3.83	4.3	0.146	0.42
Cond.	16.7	14.1	0.005	0.014	N	4.11	4.9	0.062	0.289
CO_2	16.5	13.9	0.002	0.009	Twat	3.43	4.3	0.052	0.289
Mg	11.8	9.4	0.027	0.054	Alk	1.62	2	0.459	0.614
Ca	11.6	9.2	0.058	0.089	Cond	0.88	1.1	0.49	0.614
DO	10.3	8	0.051	0.089	CO2	1.53	2	0.225	0.525
Tair	9.2	7.1	0.07	0.089	Mg	1.12	1.4	0.343	0.615
Twat	8.2	6.2	0.065	0.089	pH	0.76	1	0.481	0.615
Transp,	7.4	5.6	0.018	0.042	P	0.75	1	0.527	0.614
P	5.9	4.4	0.105	0.123	Transp	0.67	0.9	0.364	0.615
Alk	4.7	3.5	0.446	0.480	Tair	0.36	0.5	0.885	0.885
pH	1	0.7	0.812	0.812	Depth	0.3	0.4	0.867	0.885

Note: Cond. = Conductivity(μS/cm); DO = dissolved oxygen (mg/L); Transp. = transparency, Alk = alkalinity (mg/L $CaCO_3$), Tair = Air Temperature (°C); Twat = Water temperature (°C).

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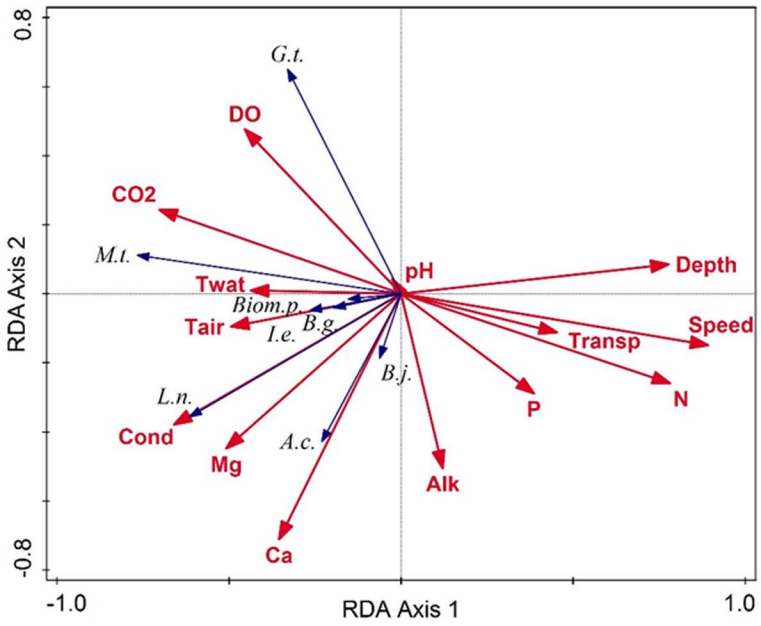


Fig 1. RDA ordination diagram depicting the relations between gastropod species' counts and all environmental predictors.

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accounting for the effects of previously selected explanatory variables) were evaluated. The results are presented in Table 1.

After the initial result, we reduced the predictors by eliminating highly correlated explanatory variables and testing combinations of subsets. The results of the Redundancy Analysis (RDA), which evaluated the relationship between the

selected environmental predictors and species composition, are ypresented in Table 2. Both simple term effects and conditional term effects were included. For N (Nitrate), the simple term effects explained 20.5% of the variance (p = 0.004). Under the conditional term effects, nitrate still explains 20.5% of the variance but with a stronger significance (p = 0.002). For conductivity, the simple term effects indicated 16.7% of the variance (p = 0.006) while the conditional term effects explained 11.1% of the variance (p = 0.007). Dissolved oxygen (DO) explained 10.3% of the variance in the simple term effect, approaching significance at p = 0.057. However, under the conditional term effect, DO explained 7.1% of the variance and was significant (p = 0.03). Water temperature explained 8.2% of the variance in the simple term effect (p = 0.058).

In the RDA diagram shown in Fig 2, all species exhibited a positive relationship with increasing water temperature (Twat), conductivity (Cond), and dissolved oxygen (DO), but a negative relationship with nitrate (N). DO was positively correlated with *Gyraulus tchadiensis* (*G.t.*), while water temperature positively influenced the abundance of several species, including (*Lymnaea natalensis* (*L.n.*), *G.t.*, *Indoplanorbis exustus* (*I.e.*), *Biomphalaria pfeifferi* (*Biom. p.*), and *Bulinus globosus* (*B.g.*). Similarly, higher conductivity predicted increase abundance of several species. By contrast, nitrate showed a negative relationship with all species, with strongest effects observed for *Melanoides tuberculata* (*M.t.*), *G. tchadiensis,* and *L. n*atalensis.

Table 2. Tested predictor effects (simple and conditional) on a selected subset of environmental variables related to the species composition within the RDA.

Simple term effects					Conditional term effects				
Variables	**Explains %**	**pseudo-F**	**P**	**P(adj)**	**Variables**	**Explains %**	**pseudo-F**	**P**	**P(adj)**
N	20.5	18.1	0.004	0.012	**N**	20.5	18.1	0.002	0.008
Cond	16.7	14.1	0.006	0.012	**Cond**	11.1	11.3	0.007	0.014
DO	10.3	8	0.057	0.058	**DO**	7.1	7.9	0.03	0.04
Twat	8.2	6.2	0.058	0.058	**Twat**	4	4.6	0.058	0.058

Note: N = Nitrate (mg/L), Cond. = Conductivity (μS/cm); DO = dissolved oxygen (mg/L); Twat = Water temperature (°C).

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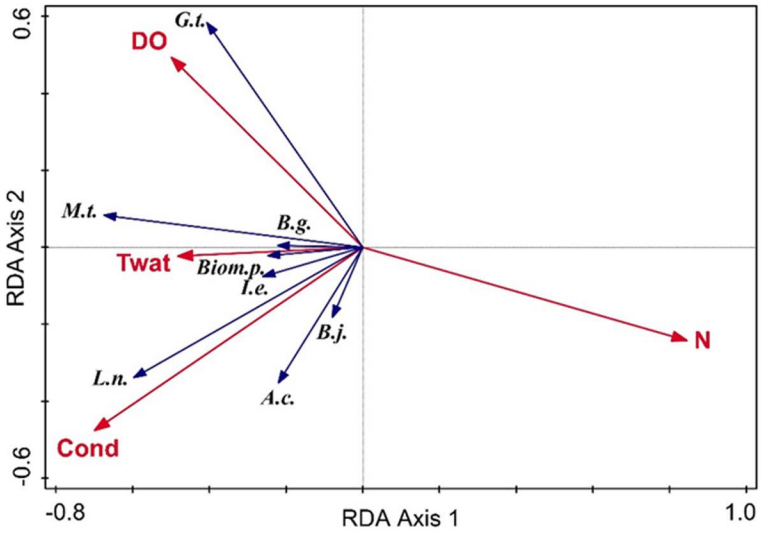


Fig 2. RDA ordination diagram of gastropod species' counts constrained by selected environmental predictors.

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3.4. Species Response Curves (SRC) - regression analyses between the species' counts and their relation to the environmental variables

In addition to the multivariate direct ordination analyses, which may mask some relationships between pairs of variables (both response and explanatory), we also examined species' responses to variations in each environmental variable separately using generalized linear models (GLMs). Fig 3 and S1 Table present the species' responses to variations in water temperature (Twat). The results showed a consistent positive relationship between species abundance with rising monthly water temperatures throughout the year. Significant linear relationships were observed for *Lymnaea natalensis* (*L.n.*), *Gyraulus tchadiensis* (*G.t.*), *Indoplanorbis exustus* (*I.e.*), *Biomphalaria pfeifferi* (*Biom.p.*), and *Bulinus globosus* (*B.g.*). The mode fit, expressed as pseudo-R^2, ranged from 7.1% ($\phi = 1.9$) for *G. tchadiensis* to 25.9% ($\phi = 2.4$) for *I. exustus* (S3 Table).

Fig 4 shows species responses to water depth, revealing significant negative relationships for seven of the eight species. The exception was *Bulinus jousseaumei* (*B.j.*), which did not exhibit any statistically significant response. With respect to transparency (Transp), five species showed significant responses (Fig 5), all demonstrating a monotonic decline in abundance with increasing water clarity. Similarly, water speed (Fig 6) had a negative influence on species abundance, aligning with pattern observed for water transparency and depth.

Fig 7 and S3 Table illustrate the effect of dissolved oxygen (DO) where *Melanoides tuberculata* (*M.t.*), *G. tchadiensis*, and *I. exustus* responded positively and significantly to increasing oxygen levels.

Although pH did not show significant effect in the RDA models, *B. globous* displayed a unimodal response in the GLM analysis, with optimal development at a pH value of 6.7 and a tolerance of 0.24 ($\phi = 2.0$) (Fig 8, S1 Table). Regarding carbon dioxide (CO_2), five species exhibited statistically significant positive relationships (Fig 9). For calcium (Ca) availability

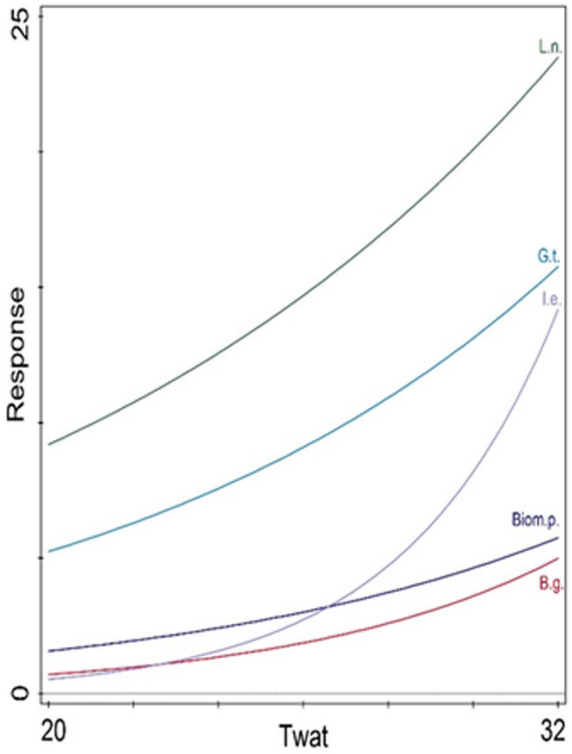


Fig 3. Species response curves (GLM) to water temperature (Twat) (°C), (only significant relations are depicted).

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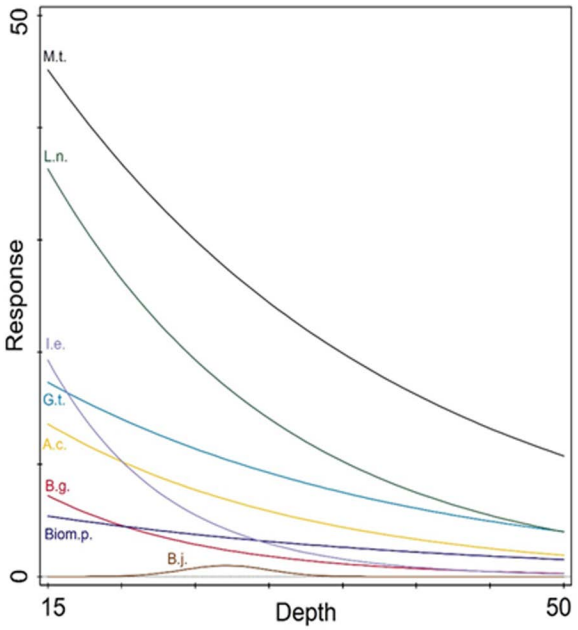


Fig 4. Species response curves (GLM) to water Depth (cm) (only significant relations are depicted).

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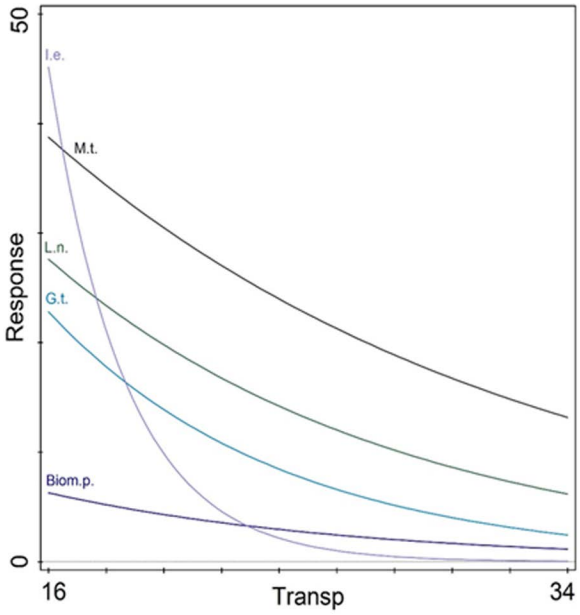


Fig 5. Species response curves (GLM) to transparency (Transp) (cm) (only significant relations are depicted).

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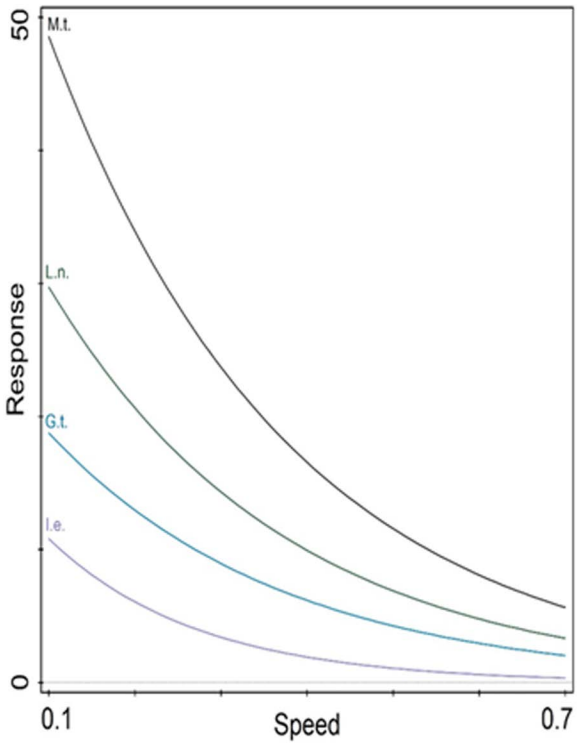


Fig 6. Species response curves (GLM) to Speed (m/s) (only significant relations are depicted).

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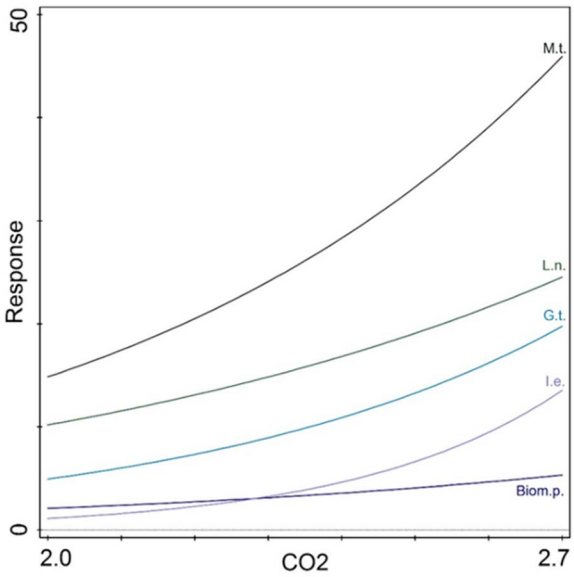


Fig 7. Species response curves (GLM) to Dissolved Oxygen (DO) (mg/L) (only significant relations are depicted).

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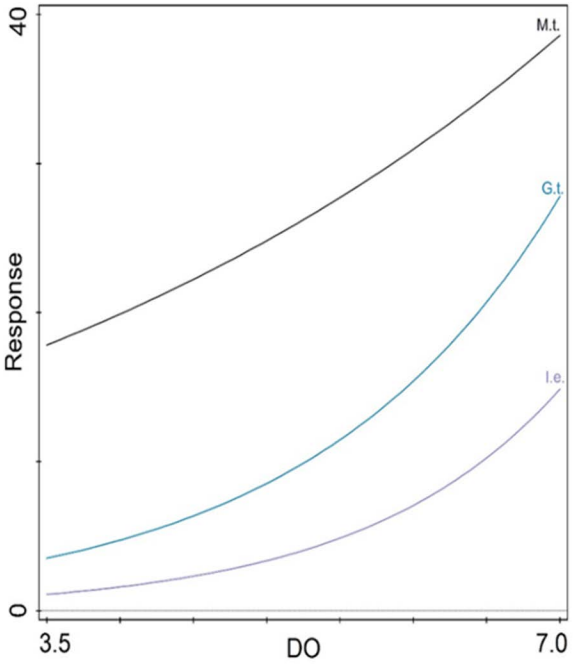


Fig 8. Species response curves (GLM) to pH (PH) (only significant relations are depicted).

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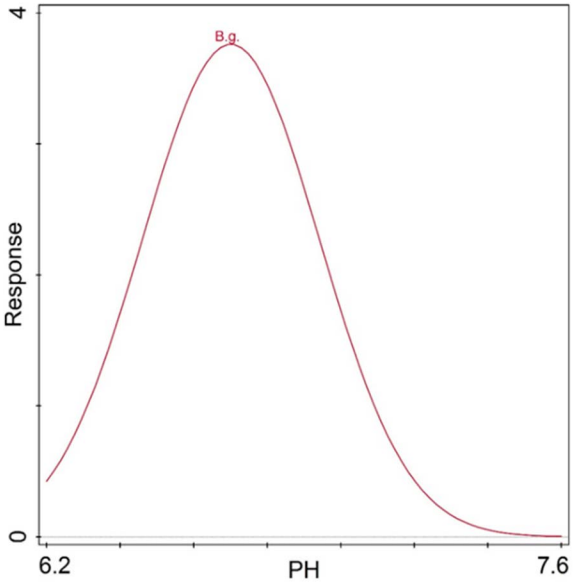


Fig 9. Species response curves (GLM) to Carbon dioxide (CO_2) (mg/L) (only significant relations are depicted).

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(Fig 10), *L. natalensis, I. exustus, Ameriana carinata* (*A.c.*), and, to a lesser extent, *Biom. pfeifferi* showed positive responses, while G. *tchadiensis* exhibited a negative response. The magnesium (Mg) gradient (Fig 11) elicited positive responses from five species, most notably from *I. exustus* and from *Biom. pfeifferi.* For nitrate (N) (Fig 12), species' responses were mixed: *G. tchadiensis* and *B. globosus* exhibited a monotonic decline, while others showed a unimodal curves, such as *M. tuberculata* ($\phi = 2.3$, pseudo-$R^2 = 44\%$) and *I. exustus* ($\phi = 2.1$, pseudo-$R^2 = 12\%$) (S1 Table). Similarly,

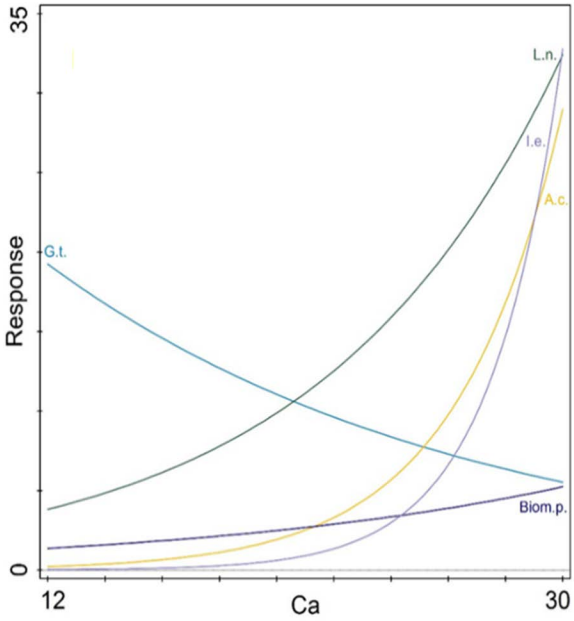


Fig 10. Species response curves (GLM) to Calcium (Ca) (mg/L) (only significant relations are depicted).

https://doi.org/10.1371/journal.pwat.0000364.g010

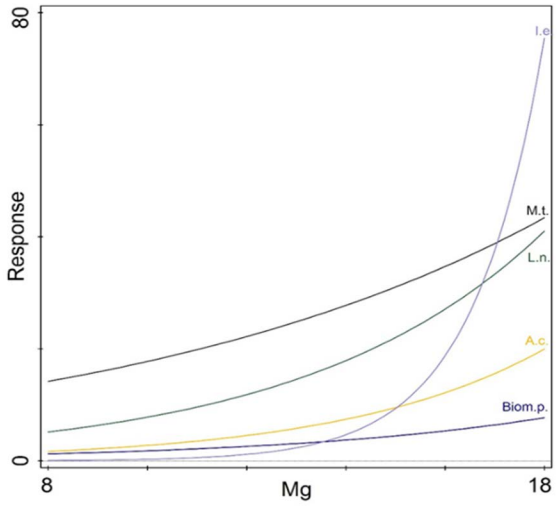


Fig 11. Species response curves (GLM) to magnesium (Mg) (mg/L) (only significant relations are depicted).

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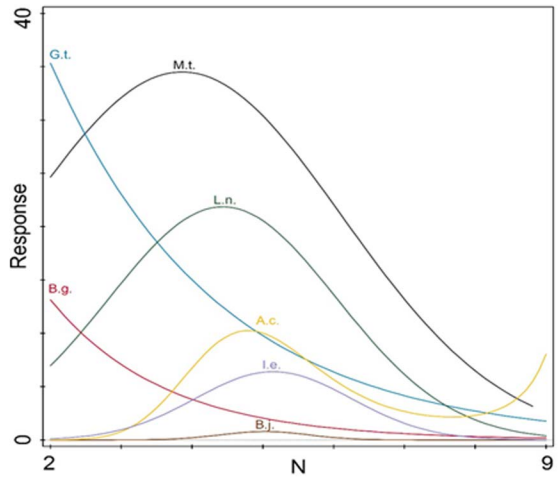


Fig 12. Species response curves (GLM) to Nitrate (N) (mg/L) (only significant relations are depicted).

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phosphorus (P) responses mirrored those of nitrate (Fig 13). *G. tchadiensis* (ϕ = 1.9) declined with increasing phosphorus, whereas *M. tuberculata, L. natalensis, A. carinata*, and *B. jousseaumei*, showed unimodal responses with varying dispersion values (ϕ = 1.6–2.3). Fig 14 shows that five species responded positively to conductivity, with *L. natalensis* exhibiting the strongest relationship (ϕ = 2.0, pseudo-R^2 = 34.5%), while the strength of the relationship was weaker for *Biom. pfeifferi*. Although alkalinity (Alk) was not significant in the multivariate analysis, GLMs (Fig 15) revealed distinct responses from three species to variations in alkalinity. The nature of these responses varied: G. *tchadiensis* exhibited a negative linear response (ϕ = 1.9), *B. globosus* a unimodal curve, and *A. carinata* a cubic pattern.

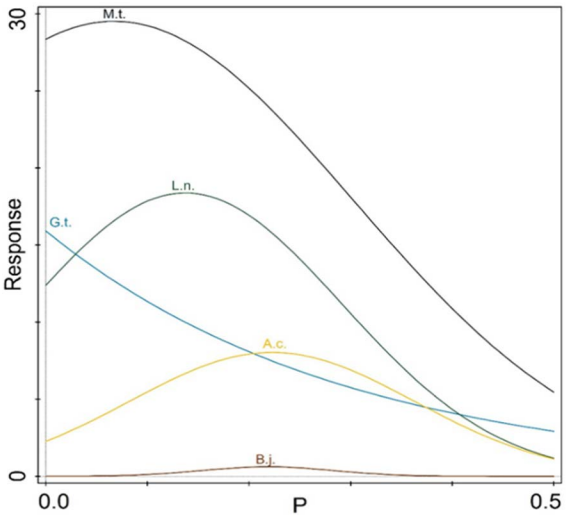


Fig 13. Species response curves (GLM) to Phosphorus (P) (mg/L) (only significant relations are depicted).

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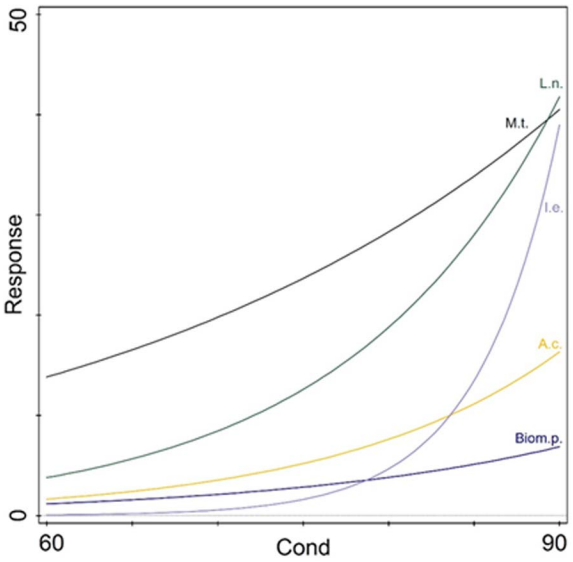


Fig 14. Species response curves (GLM) to Conductivity (Cond) (µS/cm) (only significant relations are depicted).

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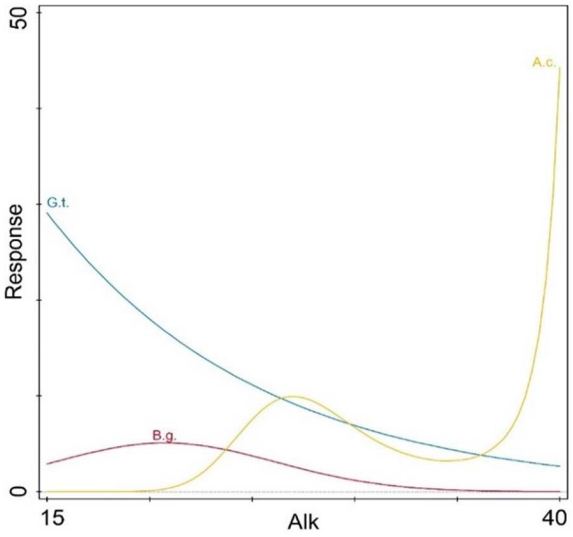


Fig 15. Species response curves (GLM) to Alkalinity (Alk) (mg/L $CaCO_3$) (only significant relations are depicted).

https://doi.org/10.1371/journal.pwat.0000364.g015

3.5. Community composition dynamics (in relation to Time)

We used Time (in numeric form) as an explanatory variable in a partial-RDA, controlling for the effect of the sampling station as a covariate. Time marginally predicted species composition ($p = 0.065$), although the effect was weak, with an adjusted explained variation of only 2.37%. Species-specific responses to time were further explored using generalized linear models (GLMs) (Table 3, detailed in S3 Table). Several species showed significant temporal trends with time (Fig 16). However, we acknowledge that this approach assumes temporal independence of observations and does not

Table 3. Statistics of GLM relating species response to Time (Time considered a quantitative predictor, sampling station considered as a covariate).

Response	Type	R^2 (%)	F	p
M. tuberculata	cubic	46.7	18.5	<0.00001
G. t.	quadratic	13	6.1	0.00374
L. n.	cubic	28.7	8	0.00012
B. g.	quadratic	28.1	7.6	0.00101
A.c	linear	7.4	5.3	0.02467
Biom. p.	linear	12	9.5	0.00298
I.I. e.	quadratic	19	7.5	0.00117

Note: *M. tuberculata – Melanoides tuberculata, G. t.- Gyraulus tchadiensis*, *B. g - Bulinus globosus, A. c - Ameriana carinata, Biom. p. - Biomphalaria pfeifferi, I. e - Indoplanorbis exustus*

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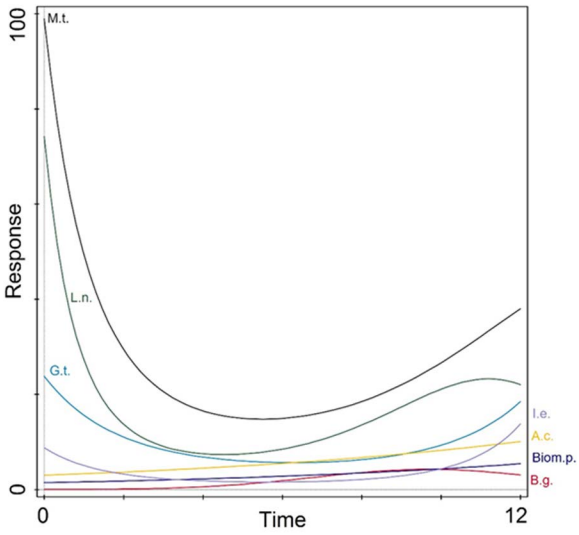


Fig 16. Species Response Curves (GLM) to Time (only significant relations are depicted).

https://doi.org/10.1371/journal.pwat.0000364.g016

explicitly account for temporal autocorrelation. Among the species, *Biom. pfeifferi*, *I. exustus.*, *A. carinata*, and *B. globosus* exhibited significant positive relationships with Time, whereas others such as *M. tuberculata*, *G. tchadiensis*, and *L. natalensis* demonstrated non-monotonic responses; however, we interpreted this cautiously (as shown in Fig 16 and Table 3).

In the second approach, we treated Time as a factorial variable (using Month as the explanatory factor) while controlling for the effect of the sampling station. This partial RDA allowed for more complex relationships beyond a simple linear model. The analysis revealed that Time had a significant effect across all axes ($p = 0.001$), with an adjusted explained variation of 41.10%. The partial-RDA ordination diagram, which accounts for the sampling station effect, is presented in Fig 17. Most species exhibited high abundance from January to April, followed by a decline towards August and October. Notably, species such as *M. tuberculata* reach peak abundance in May and declined to its minimum in October, whereas *B. jousseaumei* peaks in December and dropped to its lowest in May. The responses of species to monthly variation, as illustrated in Fig 17, offered a more nuanced understanding of their seasonal patterns and fluctuations.

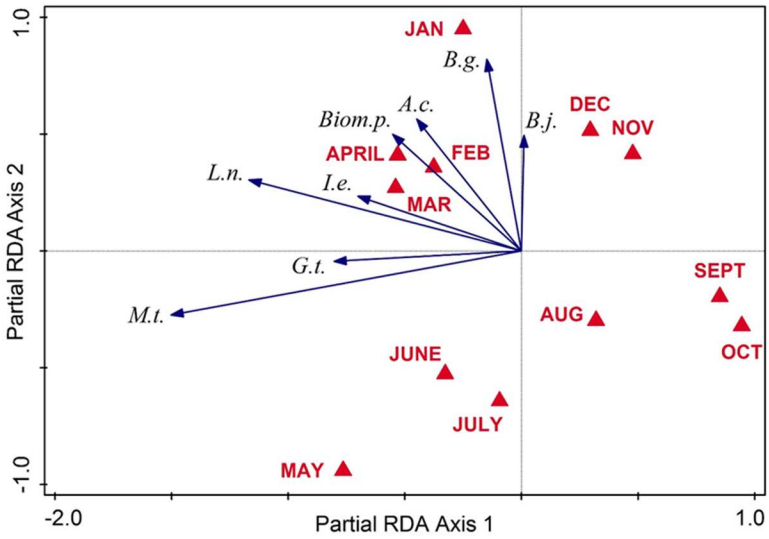


Fig 17. Partial RDA of species related to time, expressed as months (factorial variable).

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3.6. Community composition related to the sampling station

The null hypothesis posited no differences in species composition between sampling stations. To test this, we conducted an RDA using the community dataset, with sampling station as a factorial predictor, and applied a hierarchical design with a permutation scheme that controlled for the effect of time. This analysis yielded non-significant results. In contrast, the Monte Carlo permutation test with unrestricted permutations revealed statistically significant differences, as shown in Fig 18. The null hypothesis of no relationship between species composition and sampling station was rejected ($p = 0.001$,

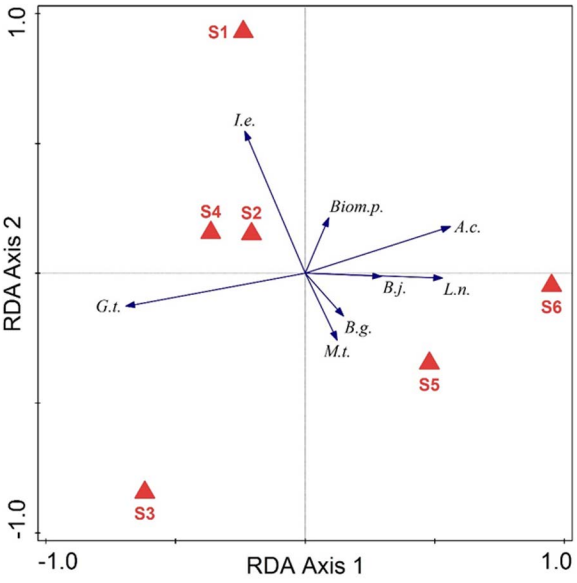


Fig 18. The RDA ordination diagram depicts the relationship between the sampling stations and species abundance.

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for all constrained axes), with an adjusted explained variation of 23.54%. This indicated that, when time effects were not controlled for (using 999 unrestricted permutations), significant differences in overall species composition existed between stations. Specifically, *I. exustus* were more abundant in the upper sections of the river, *G. tchadiensis* were more common in the middle section, while most species, including *B. globous*, *B. jousseaumei*, and *L. natalensis* showed higher abundance in the lower reaches. The species richness tended to increase downsream.

4. Discussion

Understanding the ecology and population dynamics of snail intermediate hosts at a local level is fundamental to interpreting transmission dynamics and implementing targeted control strategies for snail-borne diseases. Although urogenital schistosomiasis has been previously reported in Kwara State [21], existing studies have largely focused on parasitological indices such as infection prevalence. However, such data alone do not identify specific transmission foci or the ecological factors supporting snail population. In areas with high human movement, mapping prevalence may not accurately pinpoint the sources of infections [17]. This study advances current knowledge by examining the ecological interactions between snails and freshwater bodies, and by identifying key environmental predictors that influence their abundance in the study areas.

The study identified twelve snail species in the area, revealing a sympatric relationship within the same ecosystem. This study aligns with report of [7], who also observed the coexistence of *Bulinus* species and other planorbids in Ogun State. Among the freshwater snails identified, only the genera *Bulinus*, *Biomphalaria,* and *Lymnaea* species served as intermediate hosts for schistosomiasis and fascioliasis. Meanwhile, *Melanoides tuberculata*, which was also identified from the study areas, has been reported as a competitive species against bulinid snails in schistosome endemic regions [16]. This suggests a potential biological control strategy, provided its population can be sustainably managed or promoted in studied habitats.

The study revealed significant temporatl variations in the abundance of freshwater snails, with higher numbers observed during the dry season and lower numbers during the rainy season. Time was considered in two ways: numerically and as a categorical factor. Snail population were influenced by multiple abiotic factors; for instance, during the wet months, rising water level and increased flow rates displace snails, leading to reduced abundance. In the partial-RDA, where time was treated as a numeric variable and sampling station was controlled for, *Biom. pfeifferi*, *A. carinata*, and *B. globosus* showed significant responses to time, with their abundance increasing proportionally over the sampling period.

When time was treated as a categorical variable, using months as explanatory factors, distinct seasonal patterns in snail abundance were observed. These patterns appeared to reflect broader seasonal shifts in environmental conditions, such as changes in water temperature and nutrient levels across the year. Our observations are consistent with findings by Wepnje et al. [24] in the Mount Cameroon region, who reported increased bulinid snails abundance towards the end of the dry season. Similarly, the observed seasonal peaks in snail abundance during the dry season, particularly for bulinid species, mirror patterns reported in South Africa [11] and Chad [33].

The variation in snail abundance across different months could be attributed to seasonal changes in environmental conditions. For instance, higher counts between dry season (January to April) could correspond to periods of moderate temperatures and stable water levels, which support increased snail growth and reproduction. In contrast, the decline during peak rainy season (August to October) may reflect less favourable conditions, such as increased water flow, habitat disturbance, and cooler temperatures, all of which negatively impact snail survival and activities. Species-specific responses also contributed to these environmental variations.; For example, *M. tuberculata* may be better suited to conditions typical of the dry season, whereas *B. jousseaumei* may tolerate, or even prefer, different seasonal parameters in their abundance throughout the year. These ecological preferences help explain the differential abundance of snail species across months and highlight the complex interplay between species traits and environmental variability. The observed seasonal variation in snail abundance provides a temporal window for optimizing control efforts. Specifically, interventions

such as molluscicide and environmental modification can be strategically timed to precede or coincide with the peak of the dry season, thereby reducing snail populations before the risk of schistosomiasis transmission intensifies.

After reducing the predictors by eliminating the mostly correlated explanatory variables and using combinations of subsets, we found that conductivity, DO, and nitrate were the positive significant predictors of snails while water temperature was not. DO was positively associated with *G. tchadiensis*, suggesting that higher levels of dissolved oxygen enhance the habitat quality for this species. Snails generally require adequate oxygen levels for respiration and metabolic processes [34]. In oxygen-rich environments, *G. tchadiensis* may exhibit higher activity levels, better growth, and increased reproductive success. Increased conductivity was also associated with higher counts of several species. In contrast, nitrate was negatively related to all species, with significant affects observed for *M. tuberculata*, *G. tchadiensis,* and *L. natalensis*. Elevated nitrate levels in freshwater ecosystems have been linked in other studies to processes such as eutrophication and algal blooms, which can ultimately cause hypoxic conditions due to decomposition of excess organic matter [35]. Such water quality changes may create unfavourable conditions for snail survival, which could partly explain the reduced abundance observed in this study.

When considering the species response curves, the positive relationship between water temperature and abundance suggests that rising water temperatures may generally enhance their growth, metabolic activity, and reproductive rates. *I. exustus* appears particularly sensitive to temperature variations, potentially thriving under warmer conditions. Similarly, *B. globosus* and *Biom. pfeifferi* also responded positively to temperature, although other environmental variables also play a considerable role in their population dynamics.

Shallow or edge habitats often provide a more stable microenvironment compared to the deeper, faster-flowing parts of rivers [36]. These areas tend to be less turbulent and contains abundant organic material and vegetation, which are crucial for the survival and reproduction of many snail species. In addition, shallow zones are often less prone to extreme fluctuations in environmental conditions, making them more suitable for sustaining snail populations. In Senegal, researchers reported that dense clusters of snails were often found in deeper areas, particularly among non-emergent vegetation located away from human water access points [37]. This contrasts with our findings, where the observed negative relationship between water depth and certain species suggests that shallow environments, where food is more accessible and the risk of dislodgement by currents is reduced, are preferred by species such as *L. natalensis* and *B. globosus*. Meanwhile, the quadratic response observed in *B. jousseaumei* implies a preference for moderate depth, possibly reflecting an ecological balance where neither extreme shallowness nor great depth is optimal. The shallow microhabitats identified in this study, often created or sustained by human activities for irrigation purpose, may require targeted physical modifications or periodic drainage to effectively disrupt snail habitats without compromising their utility for human use. When tailored to local hydrological and ecological conditions, such habitat management strategies can serve as cost-effective and sustainable methods for reducing snail populations and interrupting the transmission cycle of snail-borne diseases.

The unimodal response pattern of *B. globosus* to pH and alkalinity suggests that these species have a defined ecological preference thriving best within a narrow pH range. The observed preference for slightly acidic to neutral conditions aligns with existing studies, which indicate that such a pH range supports favourable chemical and biological processes, including nutrient availability and reduced toxicity [25]. The relatively narrow tolerance range implies that *B. globosus* may be sensitive to shifts in water chemistry. Outside this optimal range, the species may experience reduced abundance due to less favourable conditions. The finding emphasizes the importance of monitoring water pH and alkalinity when designing specie-specific management strategies. Changes in pH due to environmental factors or human activities can impact the abundance and health of this species. For instance, acidification from pollution or runoff can shift pH levels away from the optimal range, potentially reducing the population of *B. globosus*.

Calcium is crucial for the growth and development of snails [38], particularly for shell formation and maintenance. In this study, the positive responses of *L. natalensis* and *Biom. pfeifferi* to calcium suggest that these species thrive in

environments with eleveated calcium levels. This observation aligns with findings from the Ethiopian Rift Valley, where calcium concentration was identified as a key factor influencing the occurrence and abundance of snail species [39]. Higher calcium levels likely provide these species with the necessary resources for robust shell development, enhancing their overall fitness and reproductive success. The high coefficient of determination indicates that *L. natalensis* has a strong dependence on calcium for its physiological and reproductive processes. This species may be particularly efficient at utilizing available calcium for shell growth and maintenance, explaining its positive response to Ca variation. Although the response of *Biomp. pfeifferi* was less pronounced, it also benefits from higher calcium levels. This suggests that, while calcium is important for its development, other factors may also play a significant role in determining its abundance.

Magnesium is essential for various physiological processes in snails, including enzyme activation, nucleic acid stability, and the functioning of the nervous system [40,41]. While calcium is the primary component of snail shells, magnesium also contributes to shell formation and structural integrity. The high coefficient of determination for *I. exustus* suggests a strong dependence on magnesium. Although the relationship was also less pronounced for *Biomp. pfeifferi*, it still exhibited a positive response to increasing magnesium concentrations. This suggests that while magnesium is beneficial to the species, *Biom. pfeifferi* might rely on a broader range of environmental factors for its development. Snail species that showed a significant positive response to magnesium may have evolved efficient mechanisms for utilizing this element. This adaptation allows them to exploit Mg-rich environments more effectively and gain a competitive advantage over species less dependent on it. Conversely, human activities that alter magnesium levels, such as agricultural runoff or industrial pollution, can impact snail populations [40].

The monotonically decreasing response of *B. globosus* to nitrate suggests that higher nitrate levels are detrimental to this species. Elevated nitrate concentrations, often resulting from agricultural runoff and pollution, can lead to eutrophication and decreased water quality [40], thereby creating unfavourable conditions for snails. *M. tuberculata* exhibits a strong unimodal response, suggesting an optimal nitrate range where its abundance peaks. This could indicate that *M. tuberculata* benefits from moderate nitrate levels, which may promote moderate algal growth, providing food without causing harmful eutrophic conditions. *B. jousseaumei* showed a quadratic response, indicating that it thrives at moderate nitrate levels but declines at both low and high extremes, implying it can tolerate a wider range of nitrate concentrations but has optimal conditions within a specific range. Similarly, *L. natalensis* showed a quadratic response, with a preference for intermediate nitrate levels, reflecting its adaptability to environments where moderate nutrient levels support balanced ecological conditions. By contrast, *I. exustus* exhibited a weaker unimodal response, suggesting that nitrate is a less critical factor for this species;however, it showed some preference for specific concentrations, indicating a degree of some sensitivity to nutrient availability.

The high coefficient of determination for *L. natalensis* suggests that this species thrives in environments with higher conductivity. The availability of dissolved ions and nutrients likely supports robust populations by promoting a healthy and productive aquatic ecosystem [42]. Increased conductivity was associated with higher counts of *L. natalensis*, indicating that this species may favour habitats with elevated ion concentrations. In this study, conductivity, as measured reflects the presence of dissolved salts and minerals, which can influence water chemistry and habitat conditions. The strong positive response of *L. natalensis* may therefore indicate a preference for more mineral-rich environments, possibly linked to enhanced habitat conditions.

Although the relationship was less pronounced in *Biom*. *pfeifferi* compared to *L. natalensis*, the former showed a positive response to increasing conductivity. This indicates that while other factors might play a more significant role in its habitat preferences, higher conductivity still contributes positively to its abundance. *Biomp. pfeifferi* may have a broader tolerance range for environmental conditions, enabling it to occupy habitats with with varying conductivity levels. However, the positive association indicates that more mineral-rich environments still provide favourable conditions for this species. In Chad, the abundance of bulinid species showed a curved pattern with conductivity, with fewer snails recorded at both the lowest and highest conductivity levels, which contracts with the pattern observed in this study [33]. These varying

responses of snail species to chemical factors highlight the importance of precision when designing control strategies. General control measures may not consistently be effective across different species. Therefore, interventions should emphasize environmentally friendly, site-specific, and species-focused approaches. Such approaches can be strengthened through community-led sanitation initiatives and improved access to safe water, thereby reducing the risk of human exposure to infested water.

5. Limitations of study

This study provides valuable insights into the ecology of schistosomiasis intermediate host snails in Edu LGA; however, the research was based on a single-year dataset, which may not fully capture year-to-year variations in snail population dynamics or shifts in environmental conditions. Snail populations, physicochemical conditions, and hydrological regimes can vary substantially between years due to climatic anomalies (e.g., droughts, floods) and long-term environmental changes. A multi-year dataset would have strengthened the temporal robustness of the findings.

In addition, while key physicochemical parameters were evaluated, the study did not incorporate a broader assessment of other potentially impactful pollutants such as heavy metals, agricultural pesticides, and industrial contaminants which may significantly alter snail community structure, either directly through toxicity or indirectly through changes in vegetation, algae, or microbial food resources.

The study was geographically limited to specific areas within Kwara State. Although this allowed for fine-scale, station-specific ecological analysis, it constrains the generalizability of the findings to other regions that may differ in hydrological patterns, climate, and levels of human activity. Furthermore, the models (for Time) used did not account for temporal autocorrelation, which may influence the reliability of the observed temporal patterns.

6. Conclusion

This study provided critical insights into the ecological dynamics of freshwater snails in Edu LGA, emphasizing their interactions with various environmental factors. Speed (water velocity) emerged as the most influential predictor of species composition, significantly impacting the distribution and abundance of snail species. Species-specific responses to factors such as dissolved oxygen, conductivity, and temperature shows the complexity of their ecological niches. These findings have direct implications for schistosomiasis control, as they highlight periods and environmental conditions that favour snail proliferation. A seasonal monitoring programme should be established to routinely track key ecological indicators, particularly water velocity, dissolved oxygen, and temperature, during the dry season when snail populations are known to peak. Integrating these environmental predictors into existing schistosomiasis surveillance and control programmes will enable early identification of high-risk habitats, support evidence-based allocation of resources, and improve the timing and effectiveness of targeted interventions. Future studies should investigate the long-term effects of climate variability on snail population dynamics and disease risk in Edu LGA. Incorporating remote sensing and geospatial tools could improve habitat prediction models and guide targeted interventions.

Supporting information

S1 Table. Monthly distribution and abundance of freshwater mollusc.
(XLSX)

S2 Table. Monthly variations of physicochemical parameters across sampling stations.
(XLSX)

S3 Table. Statistics of the GLM relating species' counts to the predictors.
(DOCX)

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Supervision: Joseph O. Sunday, Opeyemi G. Oso.

Validation: Joseph O. Sunday, Opeyemi G. Oso.

Visualization: Opeyemi G. Oso.

Writing – original draft: Joseph O. Sunday, Opeyemi G. Oso.

Writing – review & editing: Joseph O. Sunday, Opeyemi G. Oso.

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