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Land use effects on water quality, habitat, and macroinvertebrate and diatom communities in African highland streams

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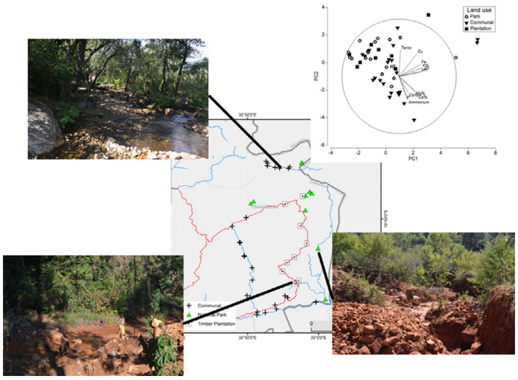
HIGHLIGHTS

- Mercury and pH were high in the national park sites.
- High phosphorus concentrations were in timber plantation and communal area sites.
- Communal and timber plantation sites were largely grouped together.
- Strong correlations were observed between diatom data and environmental variables.
- Results provide an important scientific reference for land use optimization and guidance for policy formulation.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic activities have increasingly subjected freshwater ecosystems globally to various pressures. Increasing land use activities have been highly linked to deteriorating freshwater ecosystems and dwindling biodiversity. For sound management and conservation policies to be implemented, relations between land use, environmental, and biotic components need to be widely documented. To evaluate the impacts of land use on biotic components, this study analyzed the diatom and macroinvertebrate community composition of the Eastern Highlands (Zimbabwe) streams to assess the main spatial diatom and macroinvertebrate community variances and how environmental variables and spatial factors influence community composition. Diatom and macroinvertebrate sampling was done in 16 streams in protected areas (national parks) and impacted sites (timber plantation and communal areas). Water (pH, phosphorus, and ammonium) and sediment (nitrogen, phosphorus, calcium, magnesium, manganese, and zinc) and habitat (substrate embeddedness, and habitat) variables differed significantly with land use. Principal Component Analysis (PCA) showed that the protected area had the best water quality, particularly marked by high pH levels and low phosphorus concentrations among environment types. Heavy metals were high in the communal areas, although mercury was higher in the national park. Significant differences were observed in diatom metrics, specifically dominance and

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evenness, with no significant differences observed in macroinvertebrate metrics across land uses. Diatoms differed in terms of composition in response to land use. Results provide an important scientific reference for land use optimization and guidance for the formulation of policies to protect freshwater resources in African Highland streams. Management and conservation initiatives in the Eastern Highlands are further recommended as this study detected high levels of mercury in the protected area, implying high levels of illegal mining.

1. Introduction

Water resource quality and availability in tropical watersheds are threatened by multiple anthropogenic pressures, which in turn threaten aquatic biodiversity (Carayon et al., 2020; Martins et al., 2020). Establishing the impacts of land–use changes on biotic communities in tropical streams remains an urgent goal due to increasing anthropogenic impacts in these regions (Espinoza-Toledo et al., 2021). Environmental quality assessments of tropical aquatic ecosystems are critically important for the conservation and management of water resources and for aquatic biodiversity protection (De Castro-Català et al., 2020). With the goal of protecting these vulnerable ecosystems, many national and international strategies have developed policies aimed at managing and sustaining aquatic resources. This is especially important in freshwater ecosystems, where there are increased degradation rates and species losses compared to other systems (Vörösmarty et al., 2010).

The impacts of species losses on ecosystem functioning depend on the functional roles of individual species, with extirpations leading to potential ecosystem function reductions (Cardinale et al., 2012). The association between ecosystem functioning and biodiversity is complex and depends on a multitude of factors, including community structure, environmental context, interactions among species, species loss sequence, and species traits (Birk et al., 2020). Diatoms and macroinvertebrates have been identified as important ecosystem functioning proxies, as their loss may reduce ecosystem capacity to respond to multiple stressors. Diatoms are unicellular, microscopic algae living in all aquatic environments with sufficient light (Dixit et al., 1992). Macroinvertebrates are key components of lotic ecosystems, comprising species with a high variability in terms of environmental tolerance and habitat preference (Arenas-Sánchez et al., 2021; Dalu et al., 2021; Dalu and Wasserman, 2021; Dube et al., 2021).

Unlike physical habitat structure or water chemistry, assessment of aquatic biota is a direct biological condition measure that integrates both small– and large scales, and short– and long–term anthropogenic disturbances (Mangadze et al., 2019a; Vidal et al., 2021). Biota such as diatoms, fishes, macrophytes, and macroinvertebrates are widely used in freshwater ecosystem biomonitoring, providing critical information for their protection, restoration, and sustainable use (Martins et al., 2021). Benthic diatom and macroinvertebrate communities, in particular, have been well documented to track changes in environmental conditions and human alterations within aquatic ecosystems, and, hence, are currently widely used in biomonitoring programs to evaluate water quality (Soininen, 2007; Dalu et al., 2014, 2016a; Falasco et al., 2019; Miliša et al., 2021; Sun et al., 2022). This is attributed to their short generation times (hence a rapid response to environmental shifts) and ability to integrate disturbance events, which are strongly reflected in their biomass and taxonomic composition (Dalu and Froneman, 2016; Mangadze et al., 2019a).

Metacommunity theory emphasizes the critical role of spatial processes and environmental filtering in structuring biotic communities. Several factors such as stream flow velocity and substratum composition have been identified as key diatom and macroinvertebrate composition determinants at local scales, whereas trophic condition and ion concentrations mainly influence river diatom and macroinvertebrate community changes at regional scales (Soininen, 2007; Dalu et al., 2017; Tonkin et al., 2018; Fouchy et al., 2019). Interacting multiple stressors are increasingly recognized as a major concern for species, communities, and functions, but questions remain as to what extent evidence from experiments can be transferred to field conditions and the relevance of stressor interactions for ecosystem management (Sabater et al., 2019; Birk et al., 2020). Diatom and macroinvertebrates in highland streams are exposed to multiple stressors from the surrounding environment. Quantifying how these multiple stressors affect diatom and macroinvertebrate assemblages is challenging (de Vries et al., 2019; Mangadze et al., 2019b; Dalu and Chauke, 2020; Martins et al., 2020). Thus, the characterization, identification, and understanding of the effects of these stressors are important challenges for ecologists and managers, mostly because they frequently co–occur and their interactions can cause intricate effects in aquatic communities (De Castro-Català et al., 2020).

This study analyzes diatom and macroinvertebrate community composition in Eastern Highlands (Zimbabwe) streams to assess the main spatial diatom and macroinvertebrate community variance in relation to land use activities, and also the differential role of environmental variables and spatial factors in driving the community composition in national parks/protected areas and impacted sites within the region. The hypothesis is that diatom and macroinvertebrate composition in national parks/protected area sites would mainly be shaped by spatial factors such as elevation, because the variation in physico–chemical parameters within these highland stream ecosystems is expected to be low; conversely, physico–chemical parameters would have a determinant role in anthropogenically–impacted sites. Anthropogenic impacts were expected to result in diatom and macroinvertebrate communities with reduced taxonomic diversity compared to streams with intact catchments or nearby riparian zones.

2. Materials and methods

2.1. Study area

The Eastern Highlands of Zimbabwe is a narrow mountain belt, approximately 450 km long, located on the eastern Zimbabwe–western Mozambique border (Fig. 1). The region forms part of a larger mountain chain spanning from the Ethiopian highlands (north), to the South African Drakensberg Mountains (south), with complex vegetation type mosaics including closed forests, grassland, and open woodlands (Timberlake, 1994; McGinley, 2008). The current study was done within the central region around the Chimanimani Mountains, which is suitable for coffee, tea, and dairy farming as well as exotic timber plantations. The annual rainfall range is 741–2997 mm, with most of the rain falling during the austral summer months (November to April). The mean annual temperatures range from 9 °C (winter) to 28 °C (summer) (McGinley, 2008). Freshwater diatoms, macroinvertebrates, and environmental variables were sampled and measured from 49 localities spread across three localities i.e., park (protected national areas), communal (rural areas) and plantations (timber – pine/gum) in 16 rivers and/or streams in the Chimanimani area of the Eastern Highlands, Zimbabwe towards the end of winter (12–16 July 2017; Fig. 1). Care was taken not select sites within the boundaries of any of the localities to reduce data noise and any confounding effects that might affect the interpretation of the results.

2.2. Water quality

At each sampling site, conductivity (μS cm^{-1}), pH, salinity (ppt), total dissolved solids (mg L^{-1}), and temperature (°C) were measured *in –situ* using a portable handheld multiparameter Cyberscan Series portable meter (Eutech Instruments) at two different locations spaced ~4 m apart. Water depth was measured with a graduated rod from the deepest point

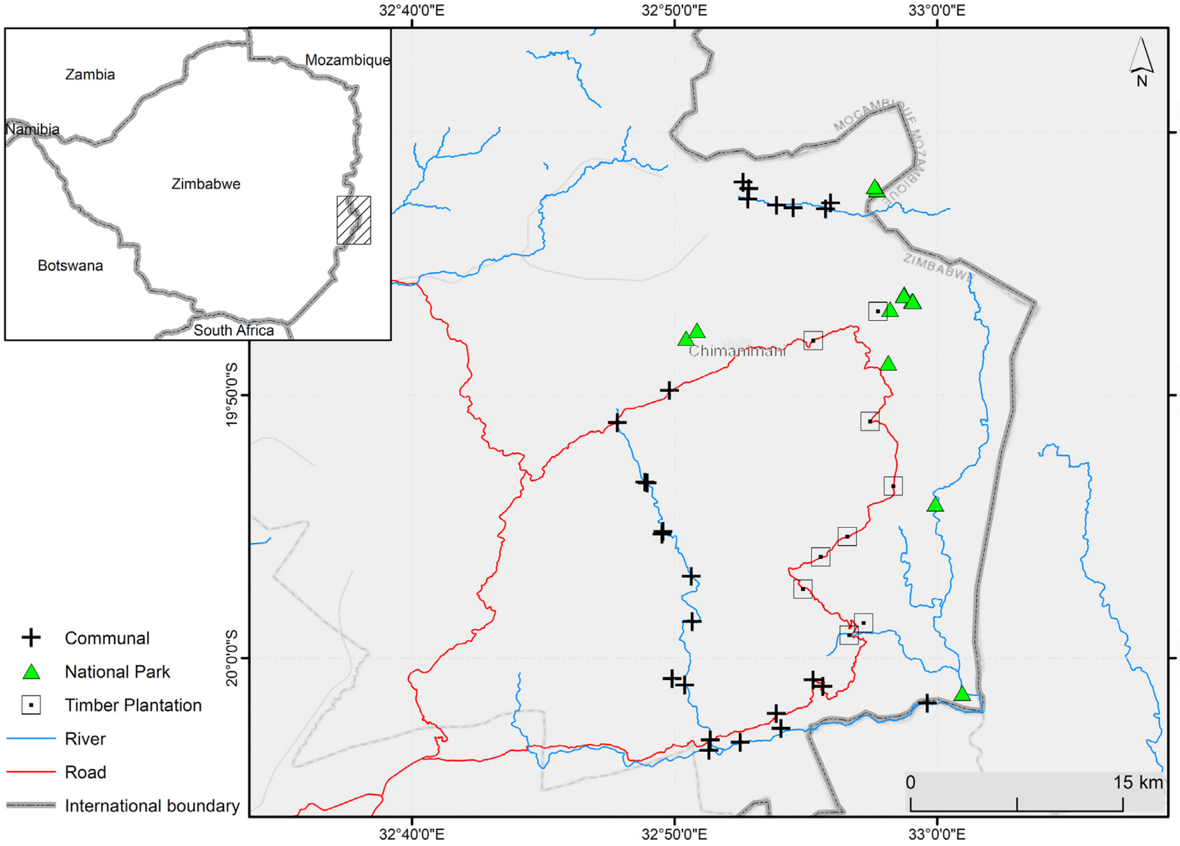

Fig. 1. Location of the study sites in the Chimanimani area in the Eastern Highlands of Zimbabwe. Node types represent different sampling sites.

of the river and/or stream. Water samples (250 mL, $n = 2$ per site) were collected in (pre–rinsed with 10 % hydrochloric acid and deionized water) polyethylene containers for nutrient phosphate ($PO^{3-}{}_4$) and ammonium ($NH^{+}{}_4$) assessment and kept on ice until sample analysis within 8 h of collection, using an HI 83203 multiparameter bench photometer (Hanna Instruments Inc., Rhode Island, US). The photometer precision accuracy range was 0–10 ± 0.05 mg L^{-1} and 0–30 ± 1 mg L^{-1} for phosphates and ammonium, respectively.

2.3. Habitat assessment

River characteristics, such as canopy cover (%), channel width (m), detrital composition cover (%), macrophyte cover (%), and substratum embeddedness were recorded at each site according to Dalu et al. (2016b). Sites were also visually assessed for obvious signs of habitat degradation associated with anthropogenic activities (i.e., illegal mining/gold panning) and pollution.

2.4. Sediment quality

Integrated 1.5 kg sediment samples from three random areas within each site were collected using acid–washed wooden splints and placed into new labelled polyethylene ziplock bags. The composite samples were immediately packed in a cooler box with ice and sent to BEMLAB, Cape Town, for analysis after being oven–dried at 60 °C for 72 h to a constant weight. Cation elements (i.e., boron (B), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na)) were fixed on with a 2:2 mixture of 2 N nitric acid (HNO_3) and hydrochloric acid at 90 °C for 35 min. Heavy metals (i.e., manganese (Mn), copper (Cu), iron (Fe), mercury (Hg), and zinc (Zn)) were analyzed using 4 g of each dried sample, with 30 mL HNO_3 (55 %) and 6 mL hydrogen peroxide (30 %) added to the sample, placed on a heated sand bed at 180 °C for 9 h, and then filtered onto a Whatman filter paper. The cation elements and heavy metal content from the extracts were determined using an inductively coupled plasma–atomic emission spectroscopy (ICP–OES) optical emission spectrometer (Varian, Mulgrave). The nitrate concentrations in the sediment were determined calorimetrically based on a SEAL Auto–Analyser 3 (Varian, Mulgrave) according to the AgriLASA (2004), whereas sediment phosphorus (sed–P) concentrations were analyzed using a Bray–2 extract method (Bray and Kurtz, 1945).

2.5. Diatoms

Diatom samples were collected by brushing from at least 10 random rocks and/or pebbles with a clean toothbrush at each site, following Taylor et al. (2005). The resulting diatom suspensions were preserved with Lugol's Iodine solution and stored in the dark until further laboratory analysis. In the laboratory, diatoms were analyzed by oxidizing organic material in samples with potassium permanganate and then hydrochloric acid (Taylor et al., 2005). Clean diatom frustules were mounted in a synthetic resin (Naphrax, refraction index = 1.73) and identified to their lowest taxonomic level, i.e., genus or species using the Taylor et al. (2007) identification guides under a phase–contrast Olympus CX light microscope at 1000 × magnification with oil immersion. A total of 300–650 valves per sample were counted according to Pappas and Stoermer (1996). Species counts were transformed into relative abundances (%) and species richness at a site was expressed as the total number of taxa identified during the inventory. The diatom species richness estimation is based on samples, and the true diatom species numbers at each site presumably is higher, as more species are likely to be encountered by counting more diatom frustules (Gotelli and Colwell, 2001).

2.6. Macroinvertebrates

Macroinvertebrates were sampled following the South African Scoring System (SASS) 5 protocol (Dickens and Graham, 2002). A nylon handheld kick net (mesh size 500 μm, dimension 30 × 30 cm) with a 1.5 m handle was used. At each sampling site, macroinvertebrates were collected by submerging the kick net, kicking benthic substratum to dislodge any attached taxa to plants and/or rocks, sweeping and dragging the net through macrophytes, along the 10 m littoral zone length transect for 5 min. The kick net was carefully lifted out of water to prevent the escape of agile animals and macroinvertebrate samples were immediately preserved in a 70 % alcohol solution in 250 mL polyethylene plastic containers after removing large detritus and plant materials. All taxa were identified and counted to family level according to field identification guides by Gerber and Gabriel (2002) and Gooderham and Tsyrlin (2002) and reported as relative abundances (%).

2.7. Data analysis

Diversity indices (richness, dominance, and Shannon diversity and evenness) were calculated using Paleontological Statistics (PAST) version 4.01 (Hammer et al., 2001) for both diatoms and macroinvertebrates. For macroinvertebrates, the total SASS score and ASPT also were calculated. The SASS 5 method awards each macroinvertebrate taxon identified on site (regardless of quantity) a score (from 1 to 15), with higher scores indicating increasing sensitivity to water quality changes. The SASS 5 score was calculated by adding individual taxon scores per sample site. The average score per taxon (ASPT) was calculated by dividing the SASS score per site with site richness. Kruskal Wallis (K–W; $p < 0.05$) tests were used to test for differences in water quality, habitat structure, and diversity indices across land uses.

Environmental data were screened for multicollinearity (Pearsons correlation analysis, $r > 0.8$). Only one environmental variable was retained in the case of collinearity. Environmental data (water quality and habitat structure) were then normalized with the exception of pH before a resemblance matrix (using Euclidian distances) was constructed. Principal component analysis (PCA) was used to visualize the environmental gradients across different land uses. Subsequently, Analysis of Similarity (ANOSIM) was used to explore whether the patterns observed had statistical significance.

Diatom and macroinvertebrate abundance data were square root transformed before non–parametric Multidimensional Scaling (*n*–MDS– using Bray–Curtis distances) was used to explore similarity of biotic communities (diatoms and macroinvertebrates) across land uses. Again, ANOSIM was subsequently used to ascertain the statistical significance of different observed patterns.

Finally, the environmental variables that best correlated with the biotic community structure were investigated using Spearman's correlation coefficient in the Primer (version 7) BioEnv program (Clarke, 1993). This procedure is similar to multiple regression and takes into consideration that often more than one environmental variable explains the structure of biological communities (Clarke, 1993). All multivariate analyses were done in PRIMER version 7.

3. Results

3.1. Variation in environmental characteristics across land uses

The values of environmental variables recorded in streams in the eastern highlands during this study are summarised in Table 1. Water phosphorus, ammonium, and pH levels, and sediment percentage nitrogen, percentage phosphorus, percentage calcium, percentage magnesium, manganese, and zinc levels varied significantly with land use (Table 1, K–W, $p < 0.05$). Mercury and pH were high in the national park (hereafter, park), while high phosphorus concentrations were found in timber plantation and communal area sites. Communal areas had significantly higher levels of water ammonium and sediment nitrogen, phosphorus, calcium, magnesium, manganese and zinc. Of the habitat variables, only substrate and habitat score significantly differed with land use (Table 1, K–W, $p < 0.05$). Substrate embeddedness was high within the park, while the habitat score was high in the timber plantations.

There were no significant differences observed in macroinvertebrate metrics across land uses (Table 1, K–W, $p > 0.05$). Significant differences were observed in the diatom metrics, specifically dominance and evenness (Table 1, K–W, $p < 0.05$). Diatom species dominance was highest in the park and lowest in the timber plantations while evenness was highest in the timber plantations and lowest in the park area.

3.2. Diatom and macroinvertebrate community structure

A total of 136 diatom taxa were identified dominated by 47 genera and 3 unidentified green algae taxa across all the study sites. However, within the park, communal and plantation sites, 102 (mean site variation (±SD) 14.6 ± 4.80), 106 (14.0 ± 3.90) and 60 (7.0 ± 1.53) taxa were identified across all study sites, respectively. Within the park sites, *Amphora copulata* (mean relative abundance 3.5 %), *Fragilaria* sp. 1 (4.5 %) and *Navicula microcephala* (3.9 %) were the most dominant taxa, whereas, in the communal sites, *Amphora coffeifformis* (3.3 %), *Diploneis smithii* (4.6 %), *Epithemia adnata* (3.5 %), *Navicula rhynchocephala* (5.2 %), *Navicula microcephala* (3.9 %), *Nitzschia dissipata* (3.1 %), *Nitzschia linearis* (3.4 %), *Rhopalodia gibberula* (3.2 %) and *Seminavis strigosa* (3.2 %) were dominant. In the plantation sites, *Amphora coffeiformis* (5.5 %), *Caloneis bacillum* (3.3 %), *Diatoma vulgaris* (3.0 %), *Diploneis smithii* (8.6 %), *E. adnata* (4.1 %), *Gyrosigma attenuatum* (3.1 %), *N. dissipata* (5.0 %) and *Nitzschia elegantula* (4.2 %) were commonest.

For the macroinvertebrates, 38 taxa were identified to at least family level, with the park, communal and plantation having 36 (mean site variation (±SD) 8.1 ± 1.53), 38 (9.0 ± 4.27) and 21 (7.0 ± 1.53) taxa, respectively. Within the park sites, Baetidae (mean relative abundance 13.7 %), Veliidae (21.7 %) and Potamonautidae (19.1 %) dominated, while, Gyrinidae (6.6 %), Baetidae (14.0 %), Hydropsychidae (5.9 %), Coenogrionidae (6.7 %), Athericidae (5.0 %) and Potamonautidae (12.3 %) were dominant in the communal sites. In the plantation sites, Gyrinidae (12.6 %), Baetidae (11.4 %), Hydropsychidae (6.9 %), Coenogrionidae (10.9 %), Tipuliidae (8.6 %) and Potamonautidae (19.4 %) were the dominant taxa.

3.3. Multivariate environmental variation across land uses

Axes 1 and 2 of the water quality PCA (Fig. 2a) explained 51.4 % of the variation in the environmental variables across different land uses. The water quality PCA distinguished between communal and park sites on Axis 2. Communal sites positively correlated with ammonium, conductivity and percentage magnesium, while park sites were positively associated with temperature, copper, mercury and pH. One–way ANOSIM pairwise comparisons showed that the differences between park and communal sites were significant (Table 2, $p = 0.009$).

Axes 1 and 2 of the habitat variables PCA (Fig. 2b) explained 57.9 % of the variation in the environmental variables across different land uses. The habitat variables PCA revealed two groupings as the communal and timber plantation sites loaded well together, being distinguished from the park sites on Axis 2. Park sites were positively associated with high macrophyte cover, canopy cover, substrate, water depth, and channel width. The communal and timber plantation sites on the other hand were associated with high habitat scores and detritus cover. One–way ANOSIM pairwise comparisons confirmed these similarities and differences (Table 2, $R = 0.131$, $p = 0.004$).

3.4. Multivariate variation in biotic communities across land uses

The diatoms *n*–MDS (Fig. 3a) revealed two site groupings. The communal and timber plantation sites were largely grouped together while the park sites grouped on their own. Pairwise comparisons revealed the significance of these groupings, showing that diatom communities in the park sites were different from those in the communal and timber plantation areas (Table 2, $p < 0.05$ in both cases) which did not differ significantly otherwise ($p = 0.54$). The macroinvertebrates *n*–MDS (Fig. 3b) did not clearly separate the sites. One–way ANOSIM ($p = 0.88$) confirmed that the macroinvertebrate communities in the different site categories were similar (Table 2, $p > 0.05$ in all pairwise comparisons).

3.5. Environmental variables associated with multivariate variation in biotic communities across land uses

The strongest correlation among diatom data and environmental variables was with pH, manganese, and copper, although the correlation was non–significant overall (Table 3, R = 0.144, $p = 0.120$). The habitat variables that best explained diatom communities were depth, substrate, and detritus cover, although the correlations were again non–significant (Table 3, R = 0.094, $p = 0.299$). The best correlation among macroinvertebrate data and water quality variables (R = 0.365, $p = 0.040$) was provided by a combination of three water quality variables (i.e., temperature, conductivity, and ammonium) and three sediment (i.e., magnesium, copper, and mercury) variables (Table 3). Lastly, the habitat variables that best explained macroinvertebrate communities (R = 0.243, $p = 0.030$) were stream width, calcium and detritus cover.

4. Discussion

4.1. Land use effects on water quality and habitat

Land use had a significant effect on water quality, with variables such as pH, phosphorus, ammonium, percentage nitrogen, percentage phosphorus, percentage calcium, percentage magnesium, manganese, and zinc differing significantly according to the environment type. However, PCA results showed that the water quality variables were only different between national park and communal area sites (Fig. 2a). As such, the park area had the best water quality, particularly marked by water with the highest pH level and lowest phosphorus among the environment types. On the other hand, communal areas had the highest levels of ammonium, percentage nitrogen, and percentage phosphorus. This is likely associated with the farming practices and fertilizer applications which are pervasive in the

Table 1

Summary of measured environmental variables and diversity metrics from different land uses in the Eastern Highlands of Zimbabwe. Kruskal–Wallis test results for the differences among the land uses. Bold values indicate $p < 0.05$.

Variable	Mean ± Standard deviation			Kruskal–Wallis *p*–value
	Park	Communal area	Timber plantation	
Water quality				
Temperature	13.98 ± 1.24	13.57 ± 2.51	14.61 ± 1.24	0.550
Dissolved oxygen	5.59 ± 1.27	5.35 ± 1.31	3.17 ± 0.2	0.070
Conductivity	37.27 ± 27.06	44.66 ± 19.89	38.18 ± 19.52	0.223
Total dissolved solids	25.45 ± 17.04	32.2 ± 14.24	28.27 ± 12.79	0.107
Salinity	22.23 ± 15.26	26.3 ± 11.09	21.26 ± 7.82	0.152
pH	8.12 ± 1.82	7.45 ± 0.22	7.34 ± 0.16	**0.025**
Phosphorus	0.4 ± 0.37	1.03 ± 0.77	0.78 ± 1.06	**0.024**
Ammonium	0.24 ± 0.2	0.62 ± 0.42	0.18 ± 0.09	**0.010**
Sediment quality				
Nitrogen (%)	0.08 ± 0.09	0.14 ± 0.08	0.07 ± 0.04	**0.007**
Phosphorus (%)	0.01 ± 0.01	0.02 ± 0	0.0 ± 0.0	**0.005**
Potassium (%)	0.02 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	**0.050**
Calcium (%)	0.07 ± 0.08	0.12 ± 0.06	0.05 ± 0.03	**0.002**
Magnesium (%)	0.05 ± 0.04	0.07 ± 0.03	0.03 ± 0.04	**0.010**
Sodium (mg kg^{-1})	110.42 ± 27.06	121.95 ± 31.79	93.31 ± 15.93	0.053
Manganese (mg kg^{-1})	543.6 ± 1383.9	742.5 ± 1065.28	375.7 ± 321.7	**0.032**
Iron (mg kg^{-1})	54,617 ± 43,257	58,324 ± 27,444	65,712 ± 65,022	0.811
Copper (mg kg^{-1})	13.6 ± 9.64	13.3 ± 13.84	16.88 ± 21.01	0.447
Zinc (mg kg^{-1})	14.43 ± 8.52	27.96 ± 27.58	16.88 ± 10.26	**0.025**
Boron (mg kg^{-1})	93.22 ± 81.61	95.71 ± 47.92	103.51 ± 100.3	0.858
Mercury (mg kg^{-1})	0.04 ± 0.07	0.01 ± 0.02	0.01 ± 0.01	0.093
Habitat variables				
Depth (m)	0.53 ± 0.3	0.34 ± 0.16	0.32 ± 0.15	0.068
Channel width (m)	5.77 ± 4.4	5.96 ± 7.03	3.61 ± 1.9	0.732
Canopy cover (%)	33.3 ± 34.4	41.8 ± 29.7	23.3 ± 32.7	0.121
Macrophyte cover (%)	60.6 ± 26.7	63.2 ± 18.2	64.4 ± 23.0	0.930
Substrate	3.9 ± 1.4	3.3 ± 1.3	2.0 ± 1.2	**0.006**
Detritus cover (%)	10.6 ± 14.2	19.7 ± 17.9	16.7 ± 12.0	0.073
Habitat score	62.8 ± 17.8	72.0 ± 14.1	100.4 ± 32.1	**0.005**
Diversity metrics				
Macroinvertebrates				
Richness	8.06 ± 1.53	9.00 ± 4.27	7.00 ± 1.53	0.389
Dominance	0.30 ± 0.24	0.27 ± 0.21	0.22 ± 0.06	0.921
Shannon diversity	1.63 ± 0.63	1.71 ± 0.62	1.69 ± 0.24	0.696
Evenness	0.72 ± 0.16	0.72 ± 0.13	0.80 ± 0.12	0.466
SASS score	40.88 ± 20.49	48.04 ± 26.78	33.57 ± 11.04	0.331
ASPT score	5.61 ± 1.45	5.69 ± 1.55	5.26 ± 1.12	0.472
Diatoms				
Richness	14.56 ± 4.80	14.00 ± 3.90	12.22 ± 2.90	0.682
Dominance	0.13 ± 0.05	0.12 ± 0.07	0.12 ± 0.04	**0.033**
Shannon diversity	2.27 ± 0.29	2.34 ± 0.35	2.30 ± 0.30	0.149
Evenness	0.71 ± 0.10	0.78 ± 0.09	0.84 ± 0.04	**0.005**

communal areas, and was expected as it has been similarly observed in several studies (Bere et al., 2016; Nhiwatiwa et al., 2017; Mwedzi et al., 2016). Heavy metals were also high in the communal areas, i.e., percentage calcium, percentage magnesium, manganese, and zinc. However, mercury was highest in the park; an observation that could have been influenced by the illegal mining activities (T.D., T.M., *pers. observation*).

Land use also led to differences in habitat structure. While several variables were not significantly different among site types, the best habitat structures were found within the park area according to the habitat score and substrate. There was significantly greater substrate embeddedness in the park owing to less human induced disturbances within the rivers. Indeed, the PCA showed that park sites were generally associated with higher riparian vegetation cover, canopy cover, substrate, river depth, and width. These findings were expected given the changes in land use and are similar to other studies (Mwedzi et al., 2017; Frainer et al., 2018). Undisturbed streams often are characterized by high habitat heterogeneity, while streams located within agricultural areas often lack diverse habitat complexity (Sawyer et al., 2004).

4.2. Biotic responses to different land uses

Despite the differences observed in water quality and habitat among the different land uses investigated, macroinvertebrate metrics did not show clear patterns following these gradients (Table 1). Accordingly, their composition did not reflect potential degradations in water and sediment qualities in the study area. However, diatom dominance and evenness responded significantly to these land use induced changes. Diatom species dominance was highest in the national park and lowest in the timber plantations, while evenness was highest in the timber plantations and lowest in the national park area. Furthermore, the diatoms *n*–MDS (Fig. 3a) analysis grouped communal and timber plantation communities together, whereas

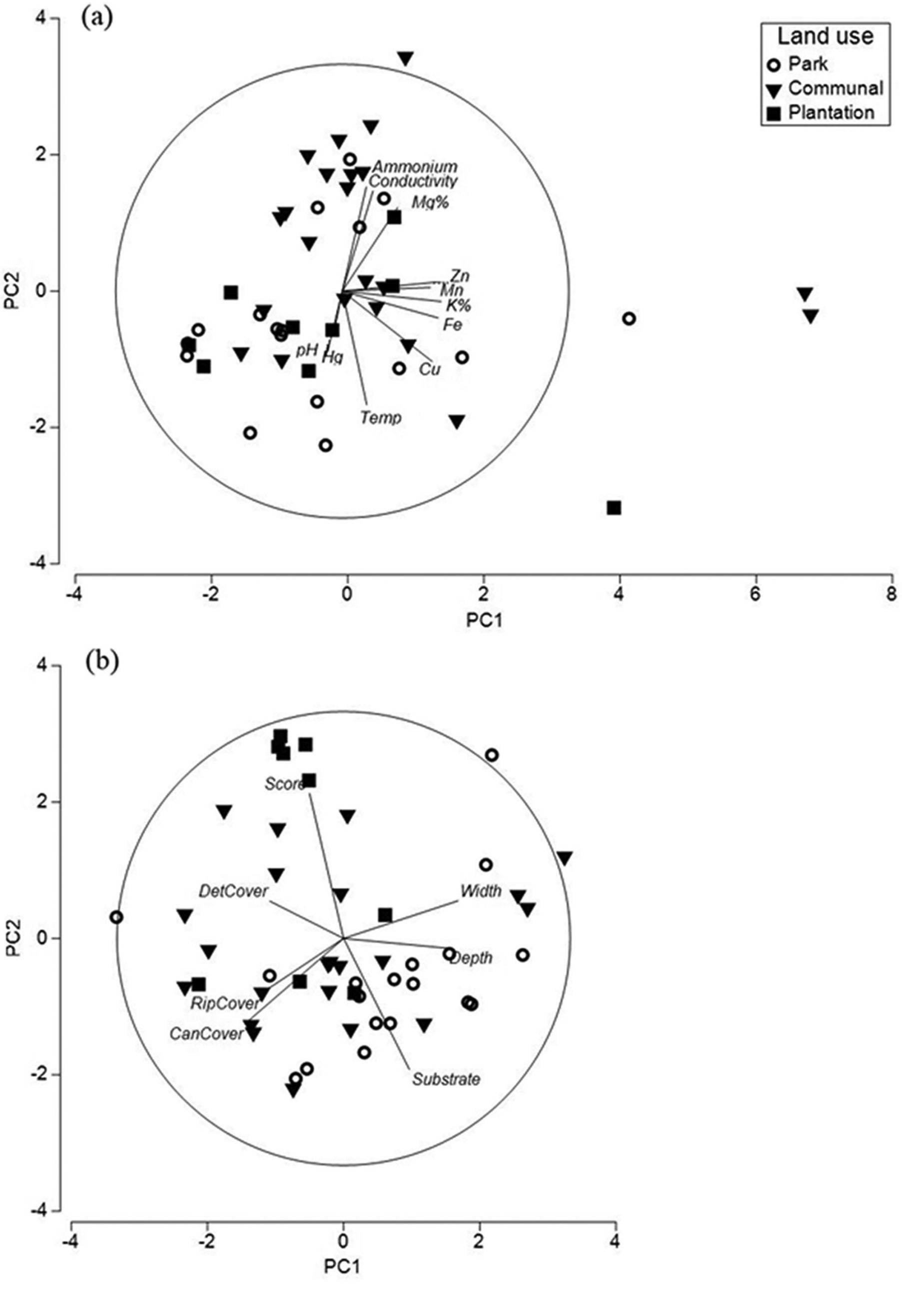

Fig. 2. Principal component analysis of (a) water quality and (b) habitat variables for the sampled rivers highlighting the relationships between the variables and study sites in the Eastern Highlands of Zimbabwe.

Table 2
ANOSIM comparisons across different land uses for environmental and biological variables within the Eastern Highlands, Zimbabwe.

Groups	R statistic	p
Water quality variables (global test, R = 0.05, p = 0.120)		
Park, Communal	0.105	**0.009**
Park, Timber plantation	−0.077	0.756
Communal, Timber plantation	0.059	0.245
Habitat variables (global test, R = 0.131, p = 0.004)		
Park, Communal	0.078	**0.046**
Park, Timber plantation	0.249	**0.007**
Communal, Timber plantation	0.134	0.065
Diatoms (global test, R = 0.167, p = 0.002)		
Park, Communal	0.228	**0.002**
Park, Timber plantation	0.242	**0.002**
Communal, Timber plantation	−0.018	0.54
Macroinvertebrates (global test, R = −0.045, p = 0.880)		
Park, Communal	−0.013	0.59
Park, Timber plantation	−0.046	0.66
Communal, Timber plantation	−0.116	0.94

the park sites grouped on their own, showing that they were different in terms of composition in response to land use.

The current findings are similar to those of Walsh and Wepener (2009) who observed that diatoms were more responsive to different land uses across the Crocodile and Magalies rivers (South Africa) compared to macroinvertebrates. In the current study, this is best understood by looking at the strongest correlations between the biotic data and the environmental variables. For instance, the best correlations between diatoms data and water quality variables were with pH, manganese, and copper. pH is well known to be important in structuring diatom communities (Antonelli et al., 2017; Bere and Tundisi, 2010) and evidently provided a distinguishing gradient in the water quality of the park sites. Considering the habitat structure variables, the best correlations (with diatoms data) were with depth, substrate, and detritus cover. Again, substrate was one of the two important habitat structure variables which distinguished park sites from the rest of the variables. On the other hand, the best correlation between macroinvertebrate data and water quality variables was provided by a combination of six variables of which only two (ammonium and magnesium) were significantly affected by land use change. In turn, most of the habitat variables that best explained macroinvertebrate communities (stream width, calcium, and detritus cover) were not significantly influenced by changes in land use. This means that the habitat variables that could have shaped

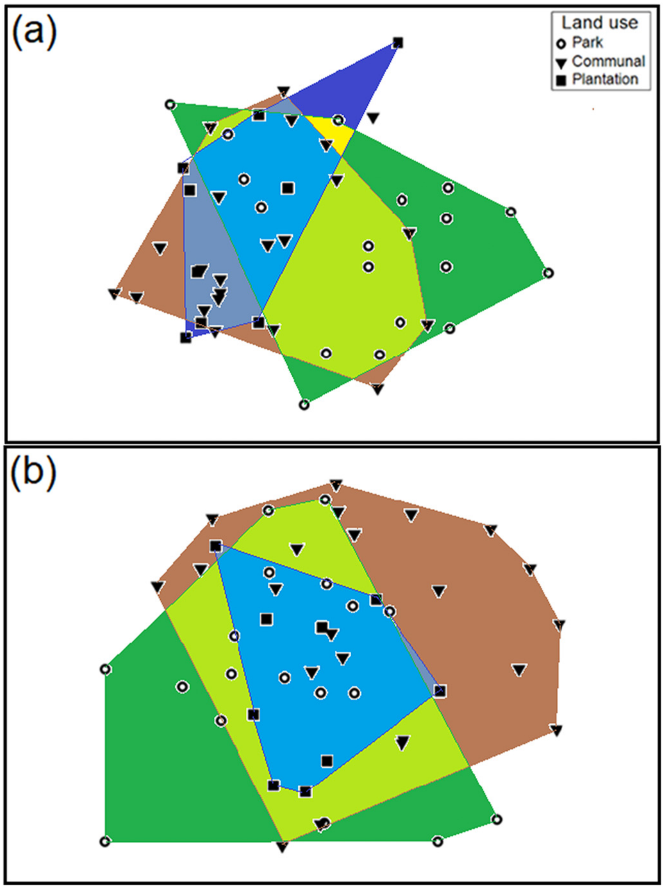

Fig. 3. Non–metric multidimensional scaling results of (a) Diatoms, and (b) macroinvertebrates showing the study locality sites in the Eastern Highlands of Zimbabwe. The polygons represent the extent of similarities of each locality over the study area.

Table 3
Best correlations between biotic communities and environmental variables (bold indicates the best match/correlations).

Number of variables	Correlation	Selections
Diatoms water quality correlations (best correlation = 0.14, p = 0.120)		
3	**0.144**	pH, manganese, copper
3	0.134	pH, iron, mercury
2	0.134	pH, iron
4	0.133	pH, manganese, copper, mercury
4	0.131	pH, potassium, iron, mercury
4	0.128	pH, manganese, iron, mercury
4	0.128	pH, potassium, magnesium, iron
3	0.127	pH, manganese, iron
4	0.127	pH, magnesium, iron, mercury
2	0.126	pH, copper
Diatoms habitat correlations (best correlation = 0.094, p = 0.299)		
3	**0.094**	Water depth, substrate, detritus cover
2	0.094	Water depth, detritus cover
4	0.091	Water depth, macrophyte cover, substrate, detritus
3	0.090	Water depth, calcium, substrate
4	0.089	Water depth, calcium, substrate, detritus
5	0.088	Water depth, calcium, macrophyte cover, substrate, detritus cover
2	0.085	Water depth, substrate
4	0.084	Water depth, calcium, macrophyte cover, substrate
3	0.081	Water depth, macrophyte cover, substrate
4	0.080	Water depth, substrate, detritus, habitat score
Macroinvertebrates water quality correlations (best correlation = 0.365, p = 0.040)		
6	**0.365**	Temperature, conductivity, ammonium, magnesium, copper, mercury
5	0.363	Temperature, ammonium, magnesium, copper, mercury
5	0.360	Temperature, conductivity, ammonium, copper, mercury
4	0.355	Temperature, ammonium, copper, mercury
6	0.350	Temperature, conductivity, ammonium, copper, zinc, mercury
6	0.35	Temperature, ammonium, magnesium, copper, zinc, mercury
6	0.344	Temperature, conductivity, ammonium, magnesium, zinc, mercury
5	0.342	Temperature, ammonium, copper, zinc, mercury
6	0.339	Temperature, ammonium, potassium, magnesium, copper, mercury
5	0.339	Temperature, ammonium, magnesium, zinc, mercury
Macroinvertebrates habitat correlations (best correlation = 0.243, p = 0.030)		
3	**0.243**	Channel width, calcium, detritus cover
4	0.237	Channel width, calcium, substrate, detritus cover
2	0.232	Channel width, detritus cover
3	0.224	Channel width, substrate, detritus cover
4	0.209	Channel width, calcium, detritus cover, habitat score
5	0.206	Channel width, calcium, substrate, detritus cover, habitat score
2	0.205	Calcium, detritus cover
3	0.199	Calcium, substrate, detritus cover
4	0.198	Depth, channel width, calcium, detritus cover

macroinvertebrate communities did not present a clear land use change gradient relative to that of diatoms.

Diatoms have been reported to give more precise data when it comes to water quality monitoring compared to macroinvertebrates (Bere and Tundisi, 2010; Mangadze et al., 2016). This is because diatoms rely on nutrient concentrations for growth, whereas macroinvertebrates rely on these nutrients indirectly, i.e., by ingesting a lower trophic level (Johnson et al., 2006). Aquatic macroinvertebrates have been demonstrated to be superior to diatoms when the gradient being investigated is hydromorphological, for example, they can reflect sedimentation in the river bed that diatoms cannot (Bere and Tundisi, 2010). In this instance, the hydromorphological gradient that could have influenced the macroinvertebrates was absent from the current study.

5. Conclusions

The current study indicates that land use change from undisturbed vegetation to agricultural land can lead to aquatic ecosystem deterioration in an understudied region of southern Africa. However, the response of organisms to such a land use change depends on the stressor gradient presented and taxonomic group considered. This study, therefore, highlights the importance of using different organisms in biomonitoring depending on the gradient presented. These findings are important as a scientific reference and should guide environmental monitoring and formulation of policies to protect freshwater resources in African Highland streams. Furthermore, there is an urgent need for management and conservation initiatives in the Eastern Highlands as this study detected high levels of mercury in the protected area, implying high levels of illegal mining.

Ethics approval

No ethical approval was required since research involved invertebrates.

Consent for publication

Not applicable, all data were collected by the authors.

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available as they are part of larger study that is currently on–going but are available from the corresponding author on reasonable request.

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CRediT authorship contribution statement

TD: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Funding acquisition, Writing – original draft, review & editing.

TM: Formal analysis, Methodology, Visualisation, Data curation, Writing – original draft, review & editing.

RNC: Visualisation, Methodology, Writing – original draft, review & editing.

RJW: Visualisation, Methodology, Writing – review & editing.

TCM: Visualisation, Methodology, Investigation, Writing – review & editing.

TN: Investigation, Visualisation, Writing – review & editing.

Declaration of competing interest

All authors declare no conflict or financial interests exist for the manuscript.

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References

Agriculture Laboratory Association of Southern Africa (AgriLASA)., 2004. Soil Handbook. Agriculture Laboratory Association of Southern Africa, Pretoria.

Antonelli, M., Wetzel, C.E., Ector, L., Teuling, A.J., Pfister, L., 2017. On the potential for terrestrial diatom communities and diatom indices to identify anthropic disturbance in soils. Ecol. Indic. 75, 73–81.

Arenas-Sánchez, A., Dolédec, S., Vighi, M., Rico, A., 2021. Effects of anthropogenic pollution and hydrological variation on macroinvertebrates in Mediterranean rivers: a case–study in the upper Tagus River basin (Spain). Sci. Total Environ. 766, 144044.

Bere, T., Tundisi, J.G., 2010. Biological monitoring of lotic ecosystems: the role of diatoms. Braz. J. Biol. 70 (3), 493–502.

Bere, T., Chiyangwa, G., Mwedzi, T., 2016. Effects of land–use changes on benthic macroinvertebrate assemblages in the tropical Umfurudzi RiverZimbabwe. Afr. J. Aquat. Sci. 41 (3), 353–357.

Birk, S., Chapman, D., Carvalho, L., Spears, B.M., Andersen, H.E., Argillier, C., Auer, S., Baattrup-Pedersen, A., Banin, L., Beklioğlu, M., Bondar-Kunze, E., 2020. Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. Nat. Ecol. Evol. 4 (8), 1060–1068.

Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59, 39–45.

Carayon, D., Eulin-Garrigue, A., Vigouroux, R., Delmas, F., 2020. A new multimetric index for the evaluation of water ecological quality of French Guiana streams based on benthic diatoms. Ecol. Indic. 113, 106248.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., 2012. Biodiversity loss and its impact on humanity. Nature 486 (7401), 59–67.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18 (1), 117–143.

Dalu, T., Froneman, P.W., 2016. Diatom–based water quality monitoring in southern Africa: challenges and future prospects. Water SA 42 (4), 551–559.

Dalu, T., Wasserman, R.J. (Eds.), 2021. Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management. Elsevier, London.

Dalu, T., Chauke, R., 2020. Assessing macroinvertebrate communities in relation to environmental variables: the case of Sambandou wetlands, Vhembe Biosphere Reserve. Appl. Water Sci. 10 (1), 1–11.

Dalu, T., Froneman, P.W., Chari, L.D., Richoux, N.B., 2014. Colonisation and community structure of benthic diatoms on artificial substrates following a major flood event: a case of the Kowie River (Eastern Cape, South Africa). Water SA 40 (3), 471–480.

Dalu, T., Froneman, P.W., Bere, T., 2016a. Assessment of water quality based on diatom indices in a small temperate river system, Kowie RiverSouth Africa. Water SA 42 (2), 183–193.

Dalu, T., Sachikonye, M.T., Alexander, M.E., Dube, T., Froneman, W.P., Manungo, K.I., Bepe, O., Wasserman, R.J., 2016b. Ecological assessment of two species of potamonautid freshwater crabs from the eastern highlands of Zimbabwe, with implications for their conservation. PloS One 11 (1), e0145923.

Dalu, T., Wasserman, R.J., Tonkin, J.D., Mwedzi, T., Magoro, M.L., Weyl, O.L., 2017. Water or sediment? Partitioning the role of water column and sediment chemistry as drivers of macroinvertebrate communities in an austral South African stream. Sci. Total Environ. 607, 317–325.

Dalu, T., Mwedzi, T., Wasserman, R.J., 2021. Phytoplankton dynamics. In: Dalu, T., Wasserman, R.J. (Eds.), Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management. Elsevier, London.

De Castro-Català, N., Dolédec, S., Kalogianni, E., Skoulikidis, N.T., Paunovic, M., Vasiljević, B., Sabater, S., Tornés, E., Muñoz, I., 2020. Unravelling the effects of multiple stressors on diatom and macroinvertebrate communities in European river basins using structural and functional approaches. Sci. Total Environ. 742, 140543.

de Vries, J., Kraak, M.H., Verdonschot, R.C., Verdonschot, P.F., 2019. Quantifying cumulative stress acting on macroinvertebrate assemblages in lowland streams. Sci. Total Environ. 694, 133630.

Dickens, C.W., Graham, P.M., 2002. The South African Scoring System (SASS) version 5 rapid bioassessment method for rivers. Afr. J. Aquat. Sci. 27, 1–10.

Dixit, S.S., Smol, J.P., Kingston, J.C., Charles, D.F., 1992. Diatoms: powerful indicators of environmental change. Environ. Sci. Technol. 26, 22–33.

Dube, T., Makaka, C.M., Mwaijengo, G.N., Mlambo, M.C., Brendonck, L., 2021. Macroinvertebrates. In: Dalu, T., Wasserman, R.J. (Eds.), Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management. Elsevier, London.

Espinoza-Toledo, A., Mendoza-Carranza, M., Castillo, M.M., Barba-Macías, E., Capps, K.A., 2021. Taxonomic and functional responses of macroinvertebrates to riparian forest conversion in tropical streams. Sci. Total Environ. 757, 143972.

Falasco, E., Bona, F., Monauni, C., Zeni, A., Piano, E., 2019. Environmental and spatial factors drive diatom species distribution in Alpine streams: implications for biomonitoring. Ecol. Indic. 106, 105441.

Fouchy, K., McClain, M.E., Conallin, J., O'Brien, G., 2019. Multiple stressors in African freshwater systems. In: Sabater, S., Arturo Elosegi, A., Ludwig, R. (Eds.), Multiple Stressors in River Ecosystems: Status, Impacts and Prospects for the Future. Elsevier, Oxford.

Frainer, A., Polvi, L.E., Jansson, R., McKie, B.G., 2018. Enhanced ecosystem functioning following stream restoration: the roles of habitat heterogeneity and invertebrate species traits. J. Appl. Ecol. 55 (1), 377–385.

Gerber, A., Gabriel, M.J.M., 2002. Aquatic Invertebrates of South African Rivers Field Guide. Institute for Water Quality Studies, Pretoria.

Gooderham, J., Tsyrlin, E., 2002. The Waterbug Book: A Guide to the Freshwater Macroinvertebrates of Temperate Australia. CSIRO Publishing, Collingwood.

Gotelli, N.J., Colwell, R.K., 2001. Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. Ecol. Lett. 4, 379–391.

Hammer, Ø., Harper, D.A., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4 (1), 9.

Johnson, R.K., Hering, D., Furse, M.T., Clarke, R.T., 2006. Detection of ecological change using multiple organism groups: metrics and uncertainty. Hydrobiologia 566, 115–137.

Mangadze, T., Bere, T., Mwedzi, T., 2016. Choice of biota in stream assessment and monitoring programs in tropical streams: a comparison of diatoms, macroinvertebrates and fish. Ecol. Indic. 63, 128–143.

Mangadze, T., Dalu, T., Froneman, P.W., 2019a. Biological monitoring in southern Africa: a review of the current status, challenges and future prospects. Sci. Total Environ. 648, 1492–1499.

Mangadze, T., Wasserman, R.J., Froneman, P.W., Dalu, T., 2019b. Macroinvertebrate functional feeding group alterations in response to habitat degradation of headwater Austral streams. Sci. Total Environ. 695, 133910.

Martins, I., Macedo, D.R., Hughes, R.M., Callisto, M., 2020. Are multiple multimetric indices effective for assessing ecological condition in tropical basins? Ecol. Indic. 110, 105953.

Martins, F.M., Feio, M.J., Porto, M., Filipe, A.F., Bonin, A., Serra, S.R., Alves, P.C., Taberlet, P., Beja, P., 2021. Assessing changes in stream macroinvertebrate communities across ecological gradients using morphological versus DNA metabarcoding approaches. Sci. Total Environ. 797, 149030.

McGinley, M., 2008. Eastern Zimbabwe montane forest–grassland mosaic. In: Cleveland, C.J. (Ed.), Encyclopedia of Earth. Environmental Information Coalition, National Council for Science and the Environment, Washington, D.C.

Miliša, M., Stubbington, R., Datry, T., Cid, N., Bonada, N., Šumanović, M., Milošević, D., 2021. Taxon–specific sensitivities to flow intermittence reveal macroinvertebrates as potential bioindicators of intermittent rivers and streams. Sci. Total Environ. 804, 150022.

Mwedzi, T., Bere, T., Mangadze, T., 2016. Macroinvertebrate assemblages in agricultural, mining, and urban tropical streams: implications for conservation and management. Environ. Sci. Pollut. Res. 23 (11), 11181–11192.

Mwedzi, T., Zimunya, T.G., Bere, T., Tarakini, T., Mangadze, T., 2017. Disentangling and ranking the influence of multiple stressors on macroinvertebrate communities in a tropical river system. Int. Rev. Hydrobiol. 102 (5–6), 103–113.

Nhiwatiwa, T., Dalu, T., Sithole, T., 2017. Assessment of river quality in a subtropical Austral river system: a combined approach using benthic diatoms and macroinvertebrates. Appl Water Sci 7 (8), 4785–4792.

Pappas, J.L., Stoermer, E.F., 1996. Formulation of a method to count number of individuals'representative of number of species in algal communities. J. Phycol. 32 (693), 196.

Sabater, S., Arturo Elosegi, A., Ludwig, R. (Eds.), 2019. Multiple Stressors in River Ecosystems: Status, Impacts and Prospects for the Future. Elsevier, Oxford.

Sawyer, J.A., Stewart, P.M., Mullen, M.M., Simon, T.P., Bennett, H.H., 2004. Influence of habitat, water quality, and land use on macro–invertebrate and fish assemblages of a southeastern coastal plain watershed, USA. Aquat. Ecosyst. Health Manag. 7 (1), 85–99.

Soininen, J., 2007. Environmental and spatial control of freshwater diatoms – a review. Diatom Res. 22 (2), 473–490.

Sun, X., Wu, N., Hörmann, G., Faber, C., Messyasz, B., Qu, Y., Fohrer, N., 2022. Using integrated models to analyze and predict the variance of diatom community composition in an agricultural area. Sci. Total Environ. 803, 149894.

Taylor, J.C., Harding, W.R., Archibald, C.G.M., 2005. A Methods Manual for the Collection, Preparation and Analysis of Diatom Samples. Version 1.0. WRC Report No. TT 281/07. Water Research Commission, Pretoria.

Taylor, J.C., Harding, W.R., Archibald, C.G.M., 2007. An Illustrated Guide to some Common Diatom Species from South Africa. Water Research Commission, Pretoria WRC Report No. TT 282/07.

Timberlake, J., 1994. Physical features of the Chirinda forest. Chirinda Forest – a visitor's guide. Forestry Commission, Harare.

Tonkin, J.D., Merritt, D.M., Olden, J.D., Reynolds, L.V., Lytle, D.A., 2018. Flow regime alteration degrades ecological networks in riparian ecosystems. Nat. Ecol. Evol. 2 (1), 86–93.

Vidal, T., Santos, M., Santos, J.I., Luís, A.T., Pereira, M.J., Abrantes, N., Gonçalves, F.J., Pereira, J.L., 2021. Testing the response of benthic diatom assemblages to common riverine contaminants. Sci. Total Environ. 755, 142534.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467 (7315), 555–561.

Walsh, G., Wepener, V., 2009. The influence of land–use on water quality and diatom community structures in urban and agriculturally stressed rivers. Water SA 35, 579–594.