



# Using the Biological Condition Gradient Model as a Bioassessment Framework to Support Rehabilitation and Restoration of the Upper Tana River Watershed in Kenya

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### Specialty section:

This article was submitted to  
Freshwater Science,  
a section of the journal  
Frontiers in Environmental Science

**Received:** 22 February 2021

**Accepted:** 14 June 2021

**Published:** 20 July 2021

### Citation:

Ndiritu GG, Terer T, Njoroge P,  
Muiruri VM, Njagi EL, Kosgei G,  
Njoroge L, Kamau PW, Malonza PK,  
Muchane M, Gathua J, Odeny D and  
Courtemanch D (2021) Using the  
Biological Condition Gradient Model as  
a Bioassessment Framework to  
Support Rehabilitation and Restoration  
of the Upper Tana River Watershed  
in Kenya.  
*Front. Environ. Sci.* 9:671051.  
doi: 10.3389/fenvs.2021.671051

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The biological condition gradient (BCG), a scientific framework that describes the change in ecosystem characteristics in response to human-induced levels of stressors, was modified and used to characterize watershed habitats in the Upper Tana River watershed, Kenya. The inbuilt utilities of BCG, including its simplicity, versatility, and its robust nature, allowed its use by seven taxonomic groups of macroinvertebrates, diatoms, fish, herpetofauna (amphibians and reptiles), plants, macrofungi, and birds to assess and monitor landscape conditions in both terrestrial and aquatic habitats. The biological data were described using taxa abundance distribution measures followed by multivariate analyses to determine their relationship with water or soil quality and thereafter assessment of taxa tolerant levels in response to environmental stress and disturbances. Preliminary findings reported that the taxonomic groups complemented each other, with each taxonomic group reliably assessing ecological conditions to a certain degree that supported assigning all 36 sampled sites into BCG tiers. The BCG models developed for all taxonomic groups assisted in the identification and selection of taxa indicating varying levels of landscape conditions. These taxa, referred to as flagship or indicator taxa, assist in simplifying the BCG model and, hence, are possible for use by parataxonomists or ordinary citizens to assess and monitor the ecological health of habitats under consideration. Furthermore, the capability of BCG models to assess landscape conditions shows how they can be used to identify important habitats for conservation, direct investment for restoration, and track progress.

**Keywords:** aquatic biodiversity, bioassessment, biomonitoring, watersheds, conservation

## INTRODUCTION

The development of a scientific-based environmental assessment and biomonitoring framework that is simple and robust enough for use by the general public remains a major limitation for sustainable management of ecosystems (Graham et al., 2004). Such a framework should be usable by the general population to monitor the ecological health of the environment, including having clear sustainable management targets to be achieved during rehabilitation and restoration initiatives (Leigh et al., 2019). The history of development and use of biological indicators show their use started with the Saprobien System (SS) concept in the early 1900s, which employed benthic macroinvertebrates and planktonic plants and animals as indicators of organic loading and low dissolved oxygen in aquatic ecosystems (Beck, 1954; Pantle and Buck, 1955; Vollenweider, 1968; Davis, 1995). The SS described the trophic state of a lake by classifying the ecological condition status along a disturbance response gradient due to pollution from human and natural influences. Today, it has evolved into indices of biotic integrity (IBIs) that are based on indices including community structure, richness, dominance and abundances as measures of pollution effects (e.g., Wilhm and Dorris, 1966; Karr, 1981; Davis 1995; Hawkins, 2006), and multivariate indices that combine weighted effects of the variates to predict membership in different water quality classes (e.g., Davies et al., 2016). Both multimetric and multivariate models use knowledge of species' natural history traits to express ecosystem changes in response to increasing levels of stressors. These ecosystem gradient models use undisturbed or pristine habitat conditions as a reference point against arrays of habitats or sites experiencing varying levels of disturbances and are validated by actual measurement of environment variables.

One biomonitoring framework that can be simplified and used for the assessment of ecological conditions is the United States Environmental Protection Agency's Biological Condition Gradient (BCG; Davies and Jackson, 2006; USEPA, 2016). The BCG is grounded on the concepts of stress ecology articulated by Odum et al. (1979), Odum (1985), Rapport et al. (1985), and Cairns et al. (1993). The BCG starts by describing the biological condition in natural or minimal disturbed habitats and the expected changes in biological conditions along a stressor gradient caused by human-induced environmental changes. Along this disturbance gradient, assemblages of taxa are selected and used to describe ecological conditions for the sites. The original BCG was developed based on common patterns of biological response to stressors observed empirically by aquatic biologists and ecologists from different geographic areas in the United States (Courtemanch et al., 1989; Courtemanch, 1995; Yoder and Rankin, 1995; Davies and Jackson, 2006). Using the practical experience of a diverse group of aquatic scientists from different biogeographic areas and independent of specific methods of assessment, the BCG is a heuristic model based on generalized observable changes in the aquatic community that can be used as a common language expressing habitat condition and change (Davies and Jackson, 2006; USEPA, 2016). The USEPA has extended the use of the

BCG concept to other aquatic habitats including coral reefs, estuaries, and mangroves.

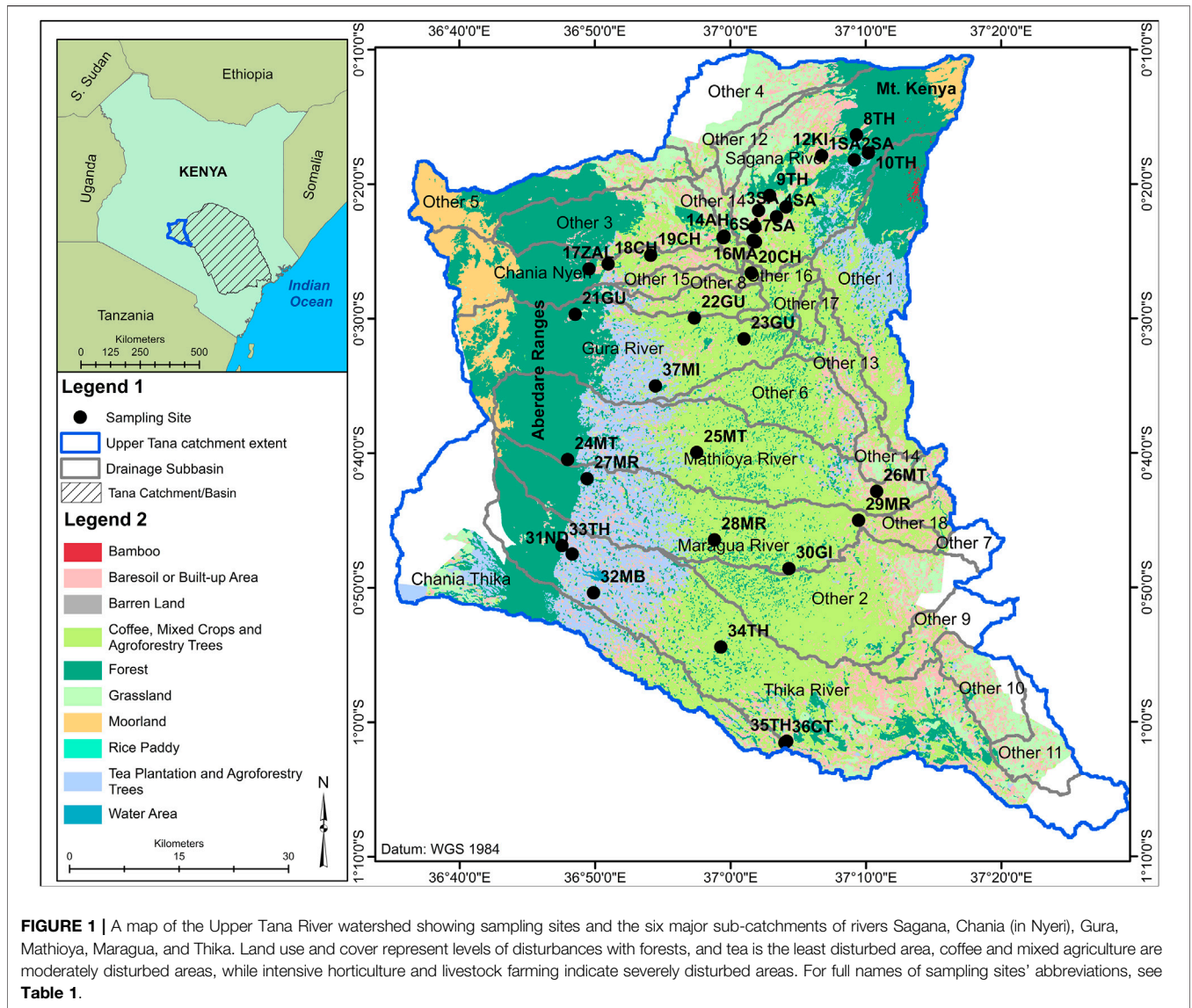
The initial use of SS, IBIs, and BCG was primarily for the monitoring and assessment of aquatic ecosystems. However, the strong links that exist between watersheds and water quality in wetlands (Masese et al., 2012; Minaya et al., 2013) suggest ecological conditions in terrestrial catchments can be used to describe the health of wetlands. As in aquatic habitats, changes in terrestrial ecological components of species composition, diversity, and ecosystems are likely to be reflected in ecosystem condition changes due to increasing levels of stress and disturbances. Therefore, the frameworks of using biological indices in monitoring and assessment of wetlands can be extended and applied in associated watersheds through using terrestrial biological components to describe ecosystems' health. The approach of integrating both aquatic and terrestrial conditions is expected to promote holistic and integrated sustainable management of landscapes that is presently being promoted as a river to the basin to the ecological network (Ishiyama et al., 2017).

## METHODS

To monitor ecological conditions of aquatic and their linked terrestrial ecosystems in the Upper Tana River (UTR) watershed, this research settled on adapting the BCG framework, which has utilities that can be used to overcome challenges of obtaining and interpreting complex scientific data for sustainable management of waters resources (Davies et al., 2016). First, the six BCG tiers were categorized and then linked to the expected set of taxonomic group responses using a subset of the BCG attributes. This was followed by the collection of biological data along disturbance gradients in both aquatic and terrestrial ecosystems. Data collected were used to describe ecological conditions of studied sites for aquatic and terrestrial taxonomic groups of macroinvertebrates, diatoms, fish, herpetofauna, vegetation, macrofungi, and birds. Relevant attributes used to develop the BCG tiers in UTR were 1) historically documented, sensitive, long-lived, or regionally endemic taxa, 2) sensitive (intolerant) taxa, 3) intermediate tolerant taxa, 4) tolerant taxa, and 5) presence of non-native species. Thereafter, collected biological data were used to assess the ecological conditions for each study site and then appropriate sustainable management interventions were proposed.

## Study Area

The UTR watershed is the upper part of the Tana River Catchment and is situated in Central Kenya. It lies between latitudes 0°30'N and 2°30'S and longitudes 37°00'E and 41°00'E. This study was undertaken in selected major rivers in Nyeri and Murang'a counties in the UTR (**Figure 1**). Both counties have an area of 4,919 km<sup>2</sup> (with Nyeri having an area of 2,361 km<sup>2</sup> and Murang'a with 2,558 km<sup>2</sup>) and a human population of 1.82 million with densities of 228 and 429 persons per km<sup>2</sup> in Nyeri and Murang'a, respectively (KNBS Kenya National Bureau of Statistics, 2019). A large percentage of



**FIGURE 1 |** A map of the Upper Tana River watershed showing sampling sites and the six major sub-catchments of rivers Sagana, Chania (in Nyeri), Gura, Mathioya, Maragua, and Thika. Land use and cover represent levels of disturbances with forests, and tea is the least disturbed area, coffee and mixed agriculture are moderately disturbed areas, while intensive horticulture and livestock farming indicate severely disturbed areas. For full names of sampling sites' abbreviations, see **Table 1**.

the land area lies between 914 and 3,000 m ASL, though a small portion comprises the high-elevation areas of Mount Kenya (3,000–5,199 m) and Aberdare Range (3,000–3,999 m). The area has an equatorial climate with two wet seasons (March–May and October–December) separated by dry seasons. The mean annual rainfall in low-lying areas is 790 mm, mid-elevations is 1,500 mm, and high-elevations is 2000 mm, while monthly mean temperature ranges from 16–20°C. Both rainfall and temperatures are functions of elevations, and the area has three major agroecological zones (AEZs) that are defined by climate, landform and soils, and land cover (FAO, 1996). The AEZ 1 represents alpine zones in the high-elevation areas, and AEZ 2 represents high-potential zones and AEZ 3 represents medium-potential zones, which are both found in the mid-elevation to low-lying areas. For instance, the AEZ 1 was confined to mountains and immediate surroundings acting as a watershed, whereas AEZ 2 was found in high-

potential areas supporting forestry, tea, livestock rearing, and tourism, while AEZ 3 supported agricultural activities of coffee, food crops, horticulture, and livestock rearing. Approximately 80% of the population depends on subsistence agriculture for livelihoods and a majority of households have small- to medium-sized farm (0.5–2 ha). Agriculture is mainly rain-fed, but recently irrigation farming is becoming more practiced due to erratic and unreliable rains. The mountainous settings are a good source of fast-flowing rivers that have created topography with steep slopes and deep valleys that influence local climate and types of crops grown. The steep topographies are prone to gully erosion and landslides. The major rivers flowing from Mt Kenya are Sagana, Thugu, and Nairobi and those from Aberdare Ranges are Honi, Muringato, Chania (in Nyeri County), Gura, Mathioya, Maragua, Thika, and Chania (bordering Murang'a and Kiambu counties). The area geology is of volcanic rocks of the Pleistocene age and Achaean type that have weathered to

give fertile soils suitable for agriculture activities. The exploitation of land and water resources has resulted in the degradation of the UTR, and the consequences are an environmental crisis that is responsible for the water insecurity issues that now threaten the social, political, and economic systems in the region (MEMR, 2012). In addition, the area is endowed with small- to medium-sized wetlands that are experiencing different levels of human use that are associated with their degradation and loss (Sakané et al., 2011).

## Sampling Design

Data on soil, water quality, and biological components were collected in the six major sub-catchments of Rivers Sagana, Chania (in Nyeri), Gura, Mathioya, Maragua, and Thika in the UTR catchment (Figure 1). For each sub-catchment, a minimum of three sampling sites were established along a disturbance gradient to represent undisturbed and then moderately to severely human-impacted areas. Overall stratified random sampling was used to select 36 permanent sites (9 sites in undisturbed, 19 in moderately disturbed, and 9 in severely disturbed areas). Sampling sites in undisturbed areas were located in the river headwaters, which had minimal human activities, and major land uses were natural forests and adjacent tea plantations. Moderately disturbed areas were found in midsections of the sub-catchments, and major types of land use were tea, coffee, zero-grazing of livestock, and moderate horticulture. Severely disturbed areas were found in the lower section of the sub-catchments, and major human activities were intensive horticultural farming and grazing of livestock in lowland floodplains and wetlands. The location coordinates of each sampling site were made using portable GPS and later aided in the mapping of species distribution and water parameters. Sampling was carried out during the end of the dry season (August–October, 2018). During this sampling regime, it was not possible to collect data for biological, water, and soil components in all sites due to logistical constraints especially time. However, efforts were made to have all components sampled in all three different land-use/-cover zones. For instance, all 36 sites were sampled for water quality and diatoms, fish were sampled in 30 sites, macroinvertebrates were sampled in 24 sites, soil parameters and macrofungi were sampled in 21 sites, vegetation was sampled in 17 sites, herpetofauna was sampled in 16 sites, and birds were sampled in 10 sites (Table 1).

## Water Quality and Flow Regimes

Electric conductivity (EC) and turbidity were measured *in situ* using portable meters (Hanna Instruments models, i.e., HI 93703d and HI 99300, respectively). Total nitrogen (TN), total phosphates (TP), and chemical oxygen demand (COD) were determined using gravimetric methods using UV-spectroscopy and natural organic matter (NOM) with a UV-light emitting diode. Water flow velocity was measured using the float method (Harrelson, 1994; Davids et al., 2019). The selection of sampled water quality parameters determined was informed by our research experience in similar habitats in tropics on those known to be affected

by effects of land-use and -cover changes (Ndaruga et al., 2004; Ndiritu et al., 2006).

## Macroinvertebrates

Samples were collected in the riffles and runs using a 500- $\mu$ m mesh size dip net. The runs and riffles' biotopes were preferred because they are the most abundant and productive biotopes in the rivers' headwaters and are known to support a great diversity of stress-sensitive taxa such as the mayflies, caddisflies, and stoneflies (Dallas, 2021). Also, it is common for rapid assessment protocols to go for a single or few biotopes. Samples were taken by dipping, jabbing, and sweeping upstream for 2 min (Barbour, 1999). Collected samples were sorted in the field, beginning with the removal of large debris, then picking all available specimens using forceps, and putting them in vials with 70% ethanol. In each site, a final simple random sampling was done from any other available biotopes (microhabitats), and the sample was combined in a separate vial for the development of a checklist. Taxonomic identification was carried out in the Invertebrate Zoology Laboratory in the National Museums of Kenya (NMK) based on morphospecies concept using standard monographs and identification keys (Day and de Moor, 2003; De Moor et al., 2003; Stals and Moor, 2007; Griffiths et al., 2015). Identification was done to order and family levels that are acceptable levels of taxonomic resolution for rapid macroinvertebrates' assessment purposes (Graham et al., 2004). Thereafter, representative specimens were vouchered and stored permanently at the Invertebrates' Collection in NMK.

## Diatoms

Samples were collected from cobbles (boulders) that were close to the riverbank from riffles (Ndiritu et al., 2006). The flowing water at the edge of the mainstream (littoral zone) is assumed to be of the same physical and chemical quality as that in the mainstream. Streams and rivers considered were from order 1–3 and most had high flow velocities that are known to reduce water quality variabilities within the cross section of a given river reach (Rode and Suhr, 2007). Diatom samples were collected from all sites where water quality variables were collected.

## Fish

Different methods were applied to sample fish depending on the suitability of the river habitats. These included hooks and line, monofilament gillnets, dip nets, and direct observations (Côté and Perrow, 2013). More information on fish was obtained by interviewing the local community within the study sites as well as checking fish collections and records at the Ichthyology Section of the NMK.

## Herpetofauna: Amphibians and Reptiles

A timed limited search (TLS) method for a one-person hour was carried out in different amphibian and reptile microhabitats in the 16 sampled sites (Malonza et al., 2011). Sampling was done during the daytime, which means amphibians especially frogs that are active at night were relatively underestimated. However, interviews were conducted in the form of questions about

amphibians and reptiles, especially those that are easy to identify and are found in the area, and this aided in increasing the body of data gathered. Local individuals were asked to describe the species and later showed the herpetofauna species pictures available in guide books (Spawls et al., 2002; Channing and Howell, 2006).

## Vegetation

Vegetation data were collected in 17 sites targeting forest remnants along the valleys and riverine systems, pine and eucalyptus woodlots, and agricultural areas. In each site, three plots of 10 m × 10 m with 300 m intervals were laid out perpendicular to both sides of the river. The data were enriched with opportunistic surveys along with road networks in farms as well as in areas outside the established study plots. Data were collected on all different plant life forms present including tree, shrubs, lianas, herbs, climbers, and epiphytes, as well as estimations of their cover, abundance, and density. Human impacts and levels of disturbances were also captured. Special attention was also given to the invasive and alien species. Vegetation identification was done using the standard floras and books including Flora of Tropical East Africa (FTEA) for various families and relevant books (Beentje, 1994; Dalitz et al., 2011; Agnew, 2013).

## Fungi

Macrofungi assemblages were sampled in riparian zones and watersheds adjacent to established permanent sampling sites. In each of the permanent sampling site, three plots 20 m × 20 m were systematically sampled along a belt transect 300 m × 20 m such that the distances between plots were approximately 100 m, with the first plot located near the river. The collection of macrofungi samples involved the use of standard sampling methods (Mueller et al., 2004). Encountered macrofungi were photographed *in situ*, and data were recorded on their densities and diversities. Representative fruit bodies were carefully collected, stored, and transported to Mycology Laboratory in the NMK for curation and preservation. The specimen was identified up to genera and species levels according to morphospecies concept using standard monographs (e.g., Harkonen et al., 2003; Ndong, et al. 2011).

## Soil Parameters

Soil samples were collected in the same sites as macrofungi and analyzed for soil organic carbon, soluble phosphorus, soil texture, and pathogenic fungi taxa of *Phytophthora*, *Fusarium*, and *Phythium*. Three 30 cm deep soil cores were collected in each of the 300 m belt transects and then mixed thoroughly to obtain a composite sample. Soil samples were analyzed following standard methods for tropical soils as described by Anderson and Ingram (1993). Soil electric conductivity was determined in water using a 1:2.5 soil solution ratio. Available phosphorus was measured using the modified Olsen's method with pH at 8.5, and soil organic carbon was measured according to the routine colorimetric dichromate oxidation method. The soil pathogens *Phytophthora*, *Fusarium*, and *Phythium* were isolated from the soil samples and then identified using morphological

characteristics of colony motif, shape, and sporangium size scanned under a light microscope at ×400 magnification.

## Birds

Three avian sampling methods, namely, point counts, mist netting, and timed species lists, were used. At least 10 point counts were conducted at intervals of 200 m along a 2 km transect (Bennun and Howell, 2002) in each sampling site. Mist netting was used in forested sites to capture the presence of skulking lower canopy and undergrowth species. The timed species counts were used to quickly build a comprehensive species list for each site as well as map species distributions following protocols of the Kenya Bird Map initiative for long-term monitoring of environmental changes at the landscape level (<http://kenyabirdmap.adu.org.za/>). We examined bird species richness along the condition gradient categorized as undisturbed (tiers 1 and 2), moderately disturbed (tiers 3 and 4), and severely degraded (tiers 5 and 6; Davies and Jackson, 2006). The data were further examined using a simple classification system for East African Forest birds developed by Bennun et al. (1996). The system goes further than a simple species list and detects subtle differences between forest avifauna in both space and time by classifying them based on their forest dependency. Thus, the classification system has three categories. 1) Forest specialists, which are the “true” forest birds’ characteristic of undisturbed forest. 2) Forest generalists, which may occur in undisturbed forest but are also regularly found in forest strips, edges, and gaps. They are likely to be relatively more common there and in the secondary forest than in the interior of intact forest. 3) Forest visitors, which are often recorded in the forest but are not dependent upon it. They are almost always more common in nonforest habitats, where they are most likely to breed. We used proportions of birds in each category in the classification system to develop indices that indicate various forest conditions (see Furness and Greenwood, 1993; Bennun et al., 1996; Bryce et al., 2002).

## Data Synthesis and Presentation

To examine patterns in the composition of taxa assemblages in relation to ecological conditions, multivariate approaches of principal component analysis (PCA), detrended correspondence analysis (DCA), and canonical correspondence analysis (CCA) were carried out (ter Braak and Šmilauer, 1999). Before PCA, DCA, and CCA analyses, the distribution model exhibited by all set of data was checked by running a DCA by default to determine whether the data had monotonic or unimodal forms of distribution. Data sets with monotonic distribution have a total length of gradients of less than four, whereas those with more than four are treated as being unimodal. All species data sets displayed unimodal types of distribution and were analyzed using either DCA or CCA, while soil and water quality had monotonic distribution and were analyzed using PCA. The indirect PCA method was used to detect changes in soil and water quality by grouping sites according to environmental conditions. The DCA is unconstrained indirect gradient analysis and grouped sites according to taxa similarities.

## The Biological Condition Gradient: Biological Response to Increasing Levels of Stress

### Levels of Biological Condition

**Level 1.** Natural structural, functional, and taxonomic integrity is preserved.

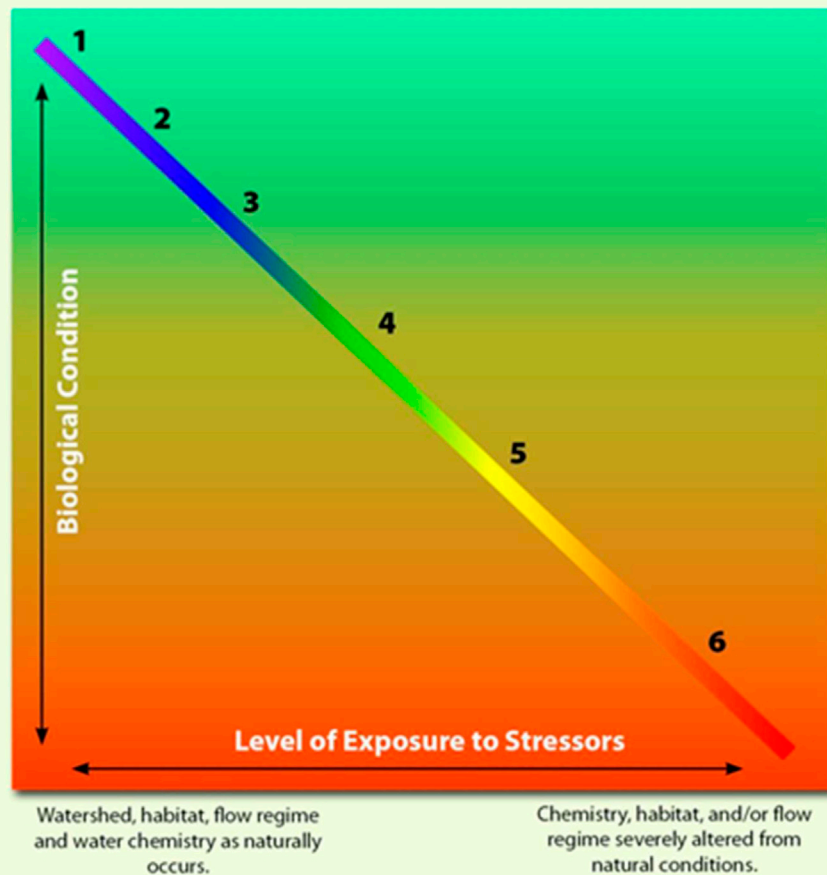
**Level 2.** Structure & function similar to natural community with some additional taxa & biomass; ecosystem level functions are fully maintained.

**Level 3.** Evident changes in structure due to loss of some rare native taxa; shifts in relative abundance; ecosystem level functions fully maintained.

**Level 4.** Moderate changes in structure due to replacement of some sensitive ubiquitous taxa by more tolerant taxa; ecosystem functions largely maintained.

**Level 5.** Sensitive taxa markedly diminished; conspicuously unbalanced distribution of major taxonomic groups; ecosystem function shows reduced complexity & redundancy.

**Level 6.** Extreme changes in structure and ecosystem function; wholesale changes in taxonomic composition; extreme alterations from normal densities.



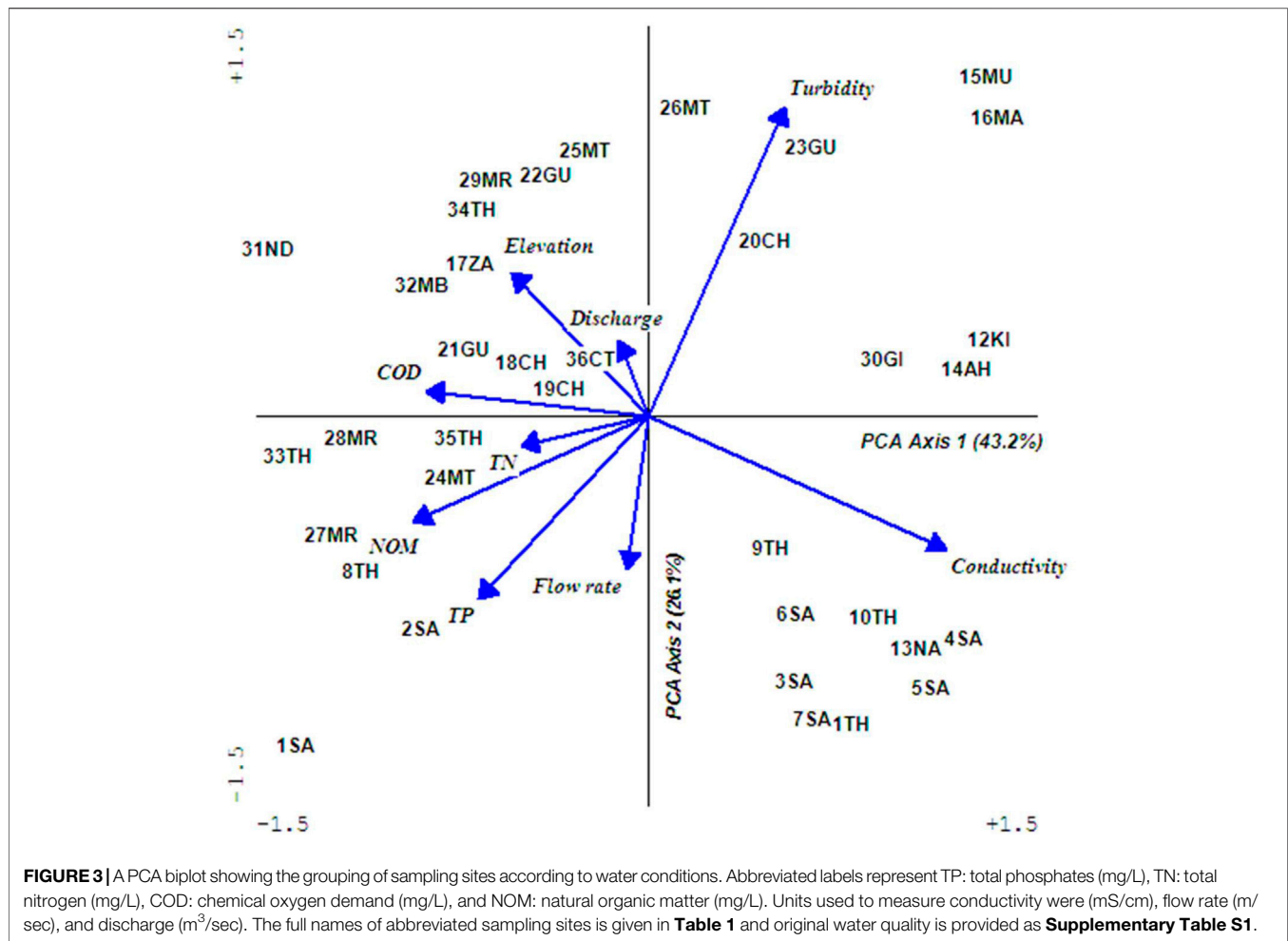
**FIGURE 2** | Conceptual model of the BCG. Although in reality, the relationship between stressors and their cumulative effects on the biota is likely nonlinear, and the relationship is presented as such to illustrate the concept (adapted from USEPA, 2016).

The biplots are interpreted indirectly by attributing the grouping of species and sites to some environmental factors. The CCA is a constrained direct gradient analysis and elucidates the relationships between biological assemblages of species and their environment (ter Braak et al., 1995). In summary, CCA is multiple linear regression that corrects for spatial autocorrelation by incorporating conditional autoregressive models and randomization test options during analyses. During these analyses, randomized 499 Monte Carlo unrestricted permutation tests under full model were performed to determine which water quality or soil variables exerted significant influences on the distribution of various biological components at  $p < 0.05$ , using conditional automatic forwarding options (Lepš and

Šmilauer, 2003). Also, the significance of the first ordination axis and all four axes together was tested. During DCA and CCA analyses, rare taxa were excluded (i.e., those that were recorded from only a single site). Meanwhile, some biological components were described using taxa abundance distribution measures of diversities and richness (Magurran 2004).

### BCG Development

The development of BCGs for the UTR commenced with the compilation and analysis of available biological data for the seven taxonomic groups. Following the USEPA's method for BCG development (USEPA, 2016), knowledge and recommendations of experts were compiled during a



workshop held in August 2018 during which experts familiar with each of the seven taxonomic groups were tasked to assess and define each of the species' preferred ecological conditions (Ndiritu et al., 2018). In this workshop, the experts used five taxonomic characteristics or attributes of taxonomic composition and community structure to develop the BCG, which included historically documented, sensitive, long-lived, or regionally endemic taxa, sensitive (intolerant) taxa, intermediate tolerant taxa, tolerant taxa, and non-native or intentionally introduced species (Davies and Jackson, 2006 in USEPA, 2016). The final phase was a field trial collection of data and observations for each of the seven taxonomic groups at some or all of the 36 established permanent sampling sites, and then experts assigning various sampling sites to the six BCG tiers using the species data collected (Davies et al., 2016). The BCG is a descriptive model that interprets changes in ecological conditions in response to human disturbance in six tiers of 1) natural or native condition, 2) minimal changes in the structure of the biotic community and minimal changes in ecosystem function, 3) evident changes in the structure of the biotic community and minimal changes in ecosystem function, 4) moderate changes

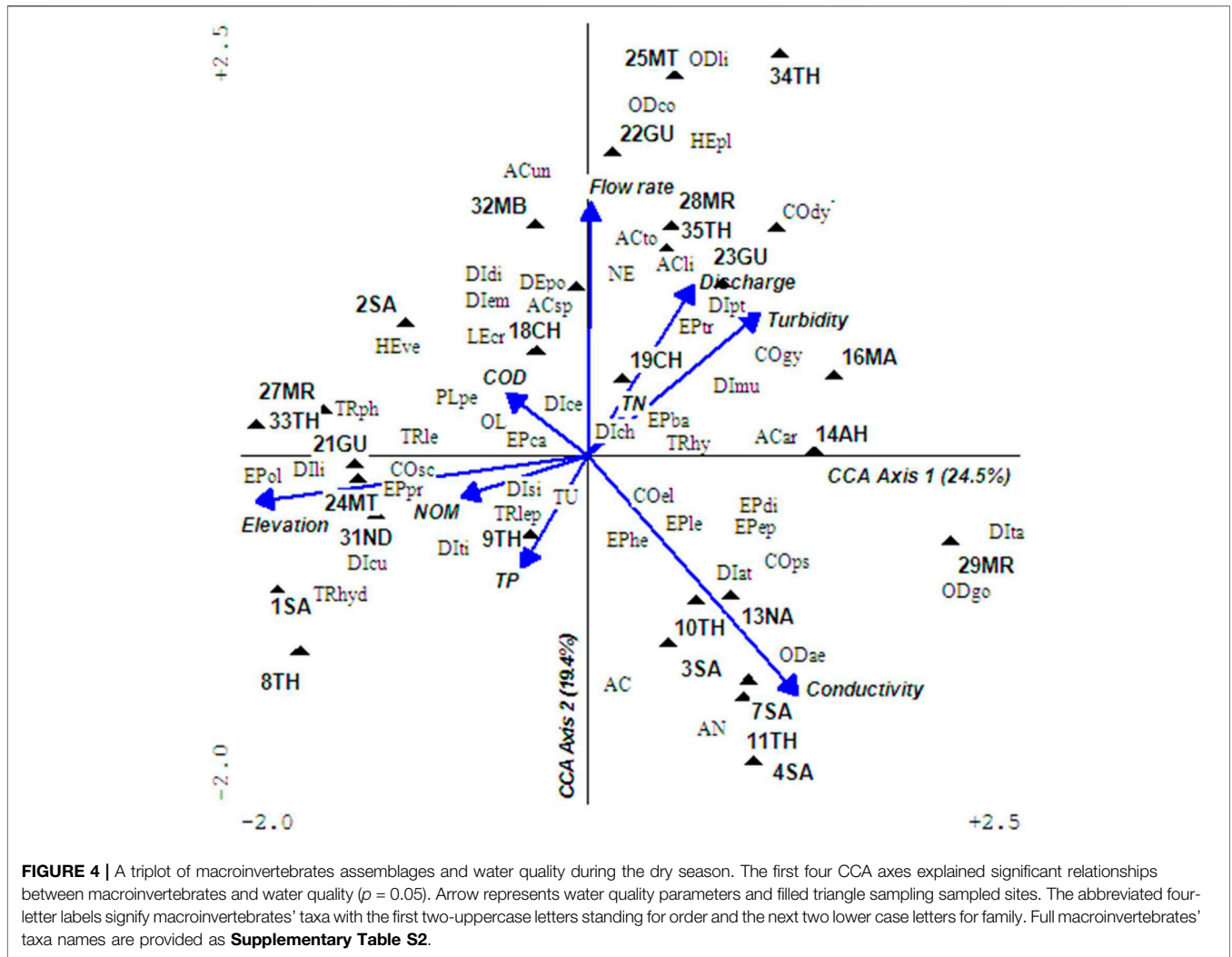
in the structure of the biotic community and minimal changes in ecosystem function, 5) major changes in the structure of the community, and 6) severe changes in the structure of the biotic community and major loss of ecosystem functions (**Figure 2**). And to the best of our knowledge, this is the first initiative where the BCG model has been used to assess ecological conditions of habitats outside the USA.

## RESULTS

### Bioassessment of Habitats in the UTR Watershed

#### Characterization of Sites Using Water Quality

Examination of ordination results revealed that water in the Upper Tana River was strongly influenced by conductivity, elevation, turbidity, and discharges (**Figure 3**). Rivers in the drier zones of Sagana catchments had low discharges but high conductivity, a situation attributed to high water abstraction, drier environments, and land-use changes. Those in Chania, Gura, Mathioya, and Maragu'a catchments were characterized



by high turbidity and water discharges in the lower sections, while the small streams in intensively farmed areas had elevated levels of TN, TP, and NOM. The headwater rivers originating from forests in Aberdare were found in higher elevations and with relatively clean water.

### Effects of Water Quality on Macroinvertebrates

The CCA analyses found most significant factors influencing macroinvertebrates were elevation ( $F = 2.77, p = 0.01$ ), conductivity ( $F = 1.94, p = 0.01$ ), and discharge ( $F = 1.84, p = 0.04$ ). The CCA grouped sampling sites along ecological condition gradients (Figure 4). All four CCA axes had a strong relationship between macroinvertebrates and water quality parameters ( $r = 0.87\text{--}0.94$ ) with the first axis having remarkable interaction with elevation and conductivity, the second axis with conductivity and flow rate, and the third axes with water discharges in rivers. A total of 51 macroinvertebrates' taxa collected from 28 sites were used to determine ecological conditions in rivers and produced interesting findings. Macroinvertebrates associated with undisturbed sites (1SA, 2SA, 8TH, 21GU, 24MT, 27MR, 31IN, and 33TH)

representing BCG tiers 1 and 2 were Scirtidae, Limoniidae, Oligoneuridae, Prosopistomatidae, Philopomatidae, and Hydroptilidae (Table 1). Macroinvertebrates somehow separated tiers 3 and 4, with tier 3 comprising sites 18CH, 22GU, 25MT, and 32MB that were characterized by high flow rates, moderate discharges, and turbidity. Indicator taxa were Sperchonidae, Unionicolidae, Potamonautidae, Dixidae, Empididae, Ceratopogonidae, Caenidae, Crambidae, Pleidae, Perlidae, Coenagrionidae, Libellulidae, and Oligochaetes, while tier 4 was represented by sites 14AH, 16MA, 19CH, 23GU, 34TH, and 35TH with high turbidity and discharges, and representative taxa were Arrenuridae, Dytiscidae, Gyrinidae, Muscidae, Ptychopteridae, Baetidae, and Trichorythidae. The lower sections of River Maragua site MR29 was classified as tier 5 with high turbidity and representative taxa were Tabanidae, Gomphidae, and Psephenidae. The mid and lower sections of Rivers Sagana, Thegu, and Nairobi had extremely low water discharge due to water abstraction that caused high conductivity levels in all the sites (3SA, 4SA, 7SA, 10TH, 11TH, and 13NA) and were placed in tier 6. Indicator taxa were Acarina, Ancylini, Psephenidae, Athericidae, and





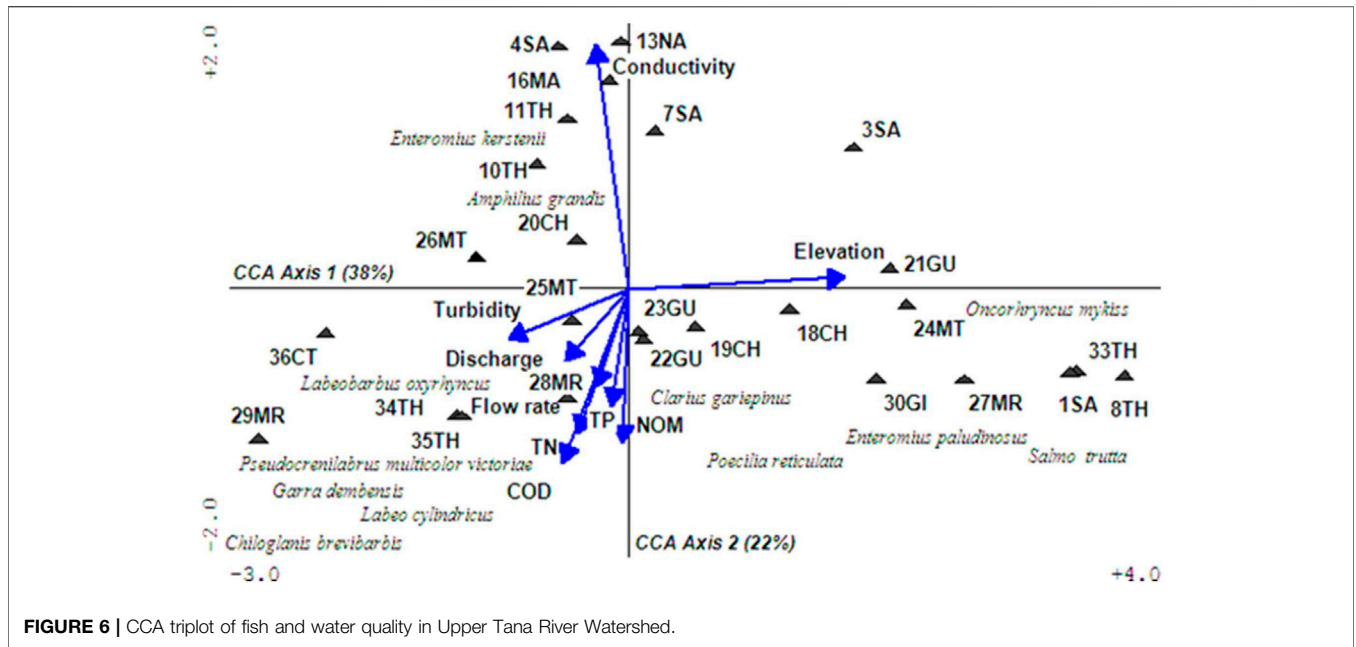


FIGURE 6 | CCA triplot of fish and water quality in Upper Tana River Watershed.

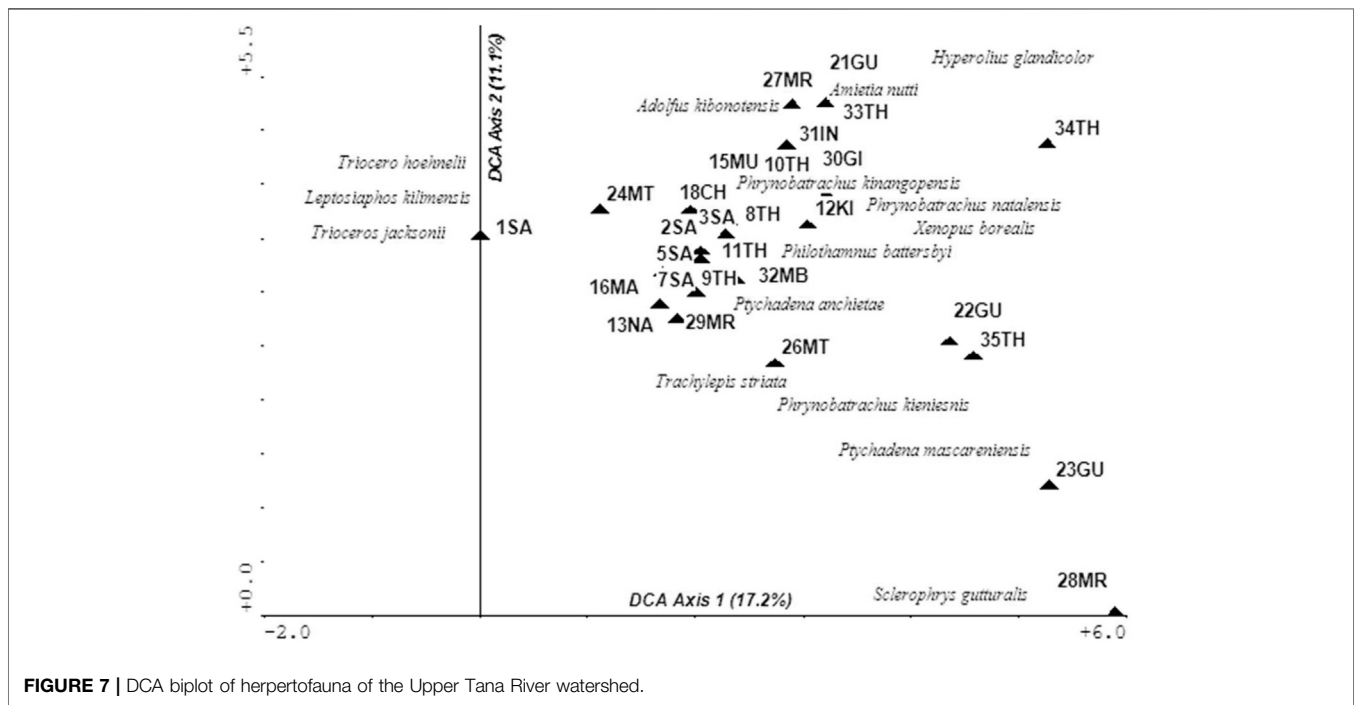


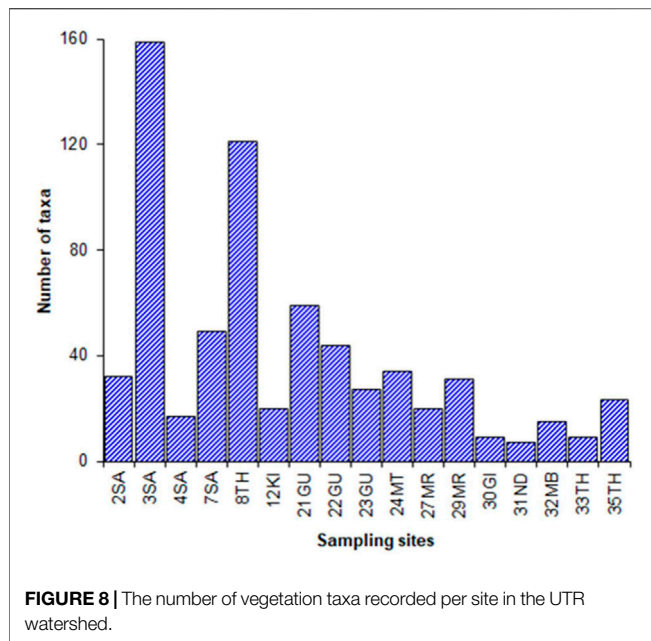
FIGURE 7 | DCA biplot of herpetofauna of the Upper Tana River watershed.

*Nitzschia frustulum*, and *N. palea*. A diatom summary of the description and categorization of sampled sites into the BCG tiers is provided in Table 1.

**Fish**

A total of 12 fish taxa were recorded from 30 sampling sites. The most common fish taxa were *Amphilius grandis* that was found in 12 sites, followed by *Enteromius kerstenii* found in 10 sites, *Garra*

*dembensis* found in 7 sites, and *Oncorhynchus mykiss* found in 6 sites, whereas *Labeobarbus oxyrhynchus* was found in 5 sites and *Poecilia reticulata* was moderately abundant in 4 sites. The other six species were occasional and in low populations. The CCA grouped sites into several groups in response to ecological conditions and were significantly influenced by elevation ( $F = 3.8, p = 0.00$ ) and conductivity ( $F = 2.31, p = 0.03$ ), Figure 6. Undisturbed sites in high-elevation areas consisted of 1SA, 8TH,



18CH, 21GU, 24MT, 27MR, and 33TH, and indicator species were *Enteromius paludinosus*, *Oncorhynchus mykiss*, and *Salmo trutta* (the latter two are introduced species). These sites were classified as tiers 1 and 2. Moderately disturbed sites were found in the mid-elevations where agriculture was the main type of land use and water ecological conditions were primarily influenced by turbidity and nutrients. Sites in this zone were 19GU, 20CH, 22GU, 23GU, 25MT, 26MT, 28MR, 29MR, 35TH, and 36CT, and fish supported were *Amphilius grandis*, *Clarius gariepinus*, *Chiloglanis brevibarbis*, *Garra dembensis*, *Labeo cylindricus*, *Pseudocrenilabrus multicolor victoriae*, *Labeobarbus oxyrhynchus*, and *Poecilia reticulata*, and sites were categorized as belonging to tiers 3 and 4. Sites 3SA, 4SA, 7SA, 10TH, 13NA, and 16MA were significantly influenced by conductivity, and the most abundant species found here (*Enteromius kerstenii* and *Amphilius grandis*) were infested with ectoparasites. The sites were categorized as severely degraded and were classified as belonging to tiers 5 and 6.

### Herpetofauna

A total of 15 herpetofauna taxa were found in 28 sites. This was a low number when compared to over 30 known taxa from the area, a situation attributed to the dry season when this group of organisms is generally dormant. In addition, no night searches were done for amphibians when they are most active. Analysis of the DCA biplot indicates that the distribution of taxa was influenced by elevation, land use, and cover (Figure 7). Taxa associated with undisturbed forests sites were found in 1SA, 21GU, 27MR, 31IN, and 33TH which were *Adolfus kibonotensis*, *Amietia nutti*, *Trioceros hoehnelii*, *T. jacksonii*, and *Leptosiaphos kilimensis*. Moderately disturbed sites such as 22GU, 23GU, 26MT, 28MR, and 35TH supported occasional to rare species such as *Ptychadena mascareniensis*, *Phrynobatrachus kieniensis*, *Scherophrys gutturalis*, *Trachylepis striata*, *Xenopus borealis*, and *Phrynobatrachus natalensis*.

*Ptychadena anchietae* and *Philothamnus battersbyi* were the most abundant and widespread species, dominating the most environmentally stressed sites in the UTR watershed of 3SA, 4SA, 7SA, 10TH, 11TH, and 13NA.

### Vegetation

Approximately 600 species were recorded from 17 sampling areas in UTR (Figure 8). A relatively high number of species were found in forest areas experiencing mild to severe disturbances in Mts Kenya and Aberdare, which implied species richness was an unreliable measure of forest ecological health. Meanwhile, the ecological conditions were evaluated using taxa composition. Both mountains supported primary and mature secondary forests, were protected, and had minimal human disturbances. Plant taxa recorded were indicators of undisturbed forest conditions and were closed canopy species such as *Impatiens tinctoria*, *Impatiens fischeri*, *Arisaema mildbraedii*, *Polystachya cultriformis*, *Begonia meyeri-johannis*, *Asplenium rutifolium*, *Asplenium theciferum*, *Asplenium hypomelas*, *Cyathea manniana*, *Eulophia horsfallii*, and *Lobelia* sp. Most of the trees in closed forests were covered by bryophytes, ferns, and orchids, another good indicator of an undisturbed environment. These sites (1SA, 8TH, 21GU, 24MT, 27MR, and 33TH) are classified as tiers 1 and 2. The midsection sites (22GU, 27MR, and 32MB) occurred in tea and coffee zones, categorized as moderately disturbed belonging to tiers 3 and 4. In addition, dominant taxa found along the riverine were represented by individuals that thrive well in secondary forests such as *Neonotonia wightii*, *Bridelia micrantha*, *Polystachya cultriformis*, and *Croton alienus*. The lower regions of UTR were dominated by farmlands, pastures, and floodplains that supported weedy species of *Achyranthes aspera*, *Commelina benghalensis*, *Vernonia lasiopous*, *Biden pilosa*, *Ageratum conyzoides*, and *Tithonia diversifolia*. The trees and shrubs included *Rhus vulgaris*, *Maytenus arbutifolia*, *Croton macrostachyus*, and *Erythrina abyssinica*, whereas the swampy areas were dominated by *Typha domingensis*, *Cyperus dichrostachyus*, *Ludwigia stolonifera*, *Lemna gibba*, *Centella asiatica*, and *Rumex bequeritii*. Alien and invasive species were recorded in the disturbed areas and these included *Ricinus communis*, *Verbena bonariensis*, *Lantana camara*, and *Datura stramonium*.

### Macrofungi Community and Soil Parameters

Results of PCA using relevant soil parameters grouped sampling sites according to their conditions with SOC and soluble phosphate decreasing downstream (Figure 9A). Similarly, *Phytophthora* and *Fusarium* abundances increased in degraded agricultural soils, while *Phythium* was associated with soils with minimal disturbances. A total of 88 genera of macrofungi were recorded from 21 samples in UTR. Further analysis of CCA using 55 genera (that were occasional to abundant in occurrences) found that elevation ( $F = 1.53$ ,  $p = 0.01$ ) and soluble phosphorus ( $F = 1.4$ ,  $p = 0.05$ ) significantly interacted with macrofungi with elevation mildly correlating with CCA axis 1 ( $r = -0.5$ ) and soluble phosphorus strong with CCA axis 2 ( $r = 0.7$ ). However, no clear patterns were observed and macrofungi

**TABLE 1** | Characterizing sampling sites into tiers using water quality, soil parameters, and various taxonomic groups (–) = signify no data or inadequate data.

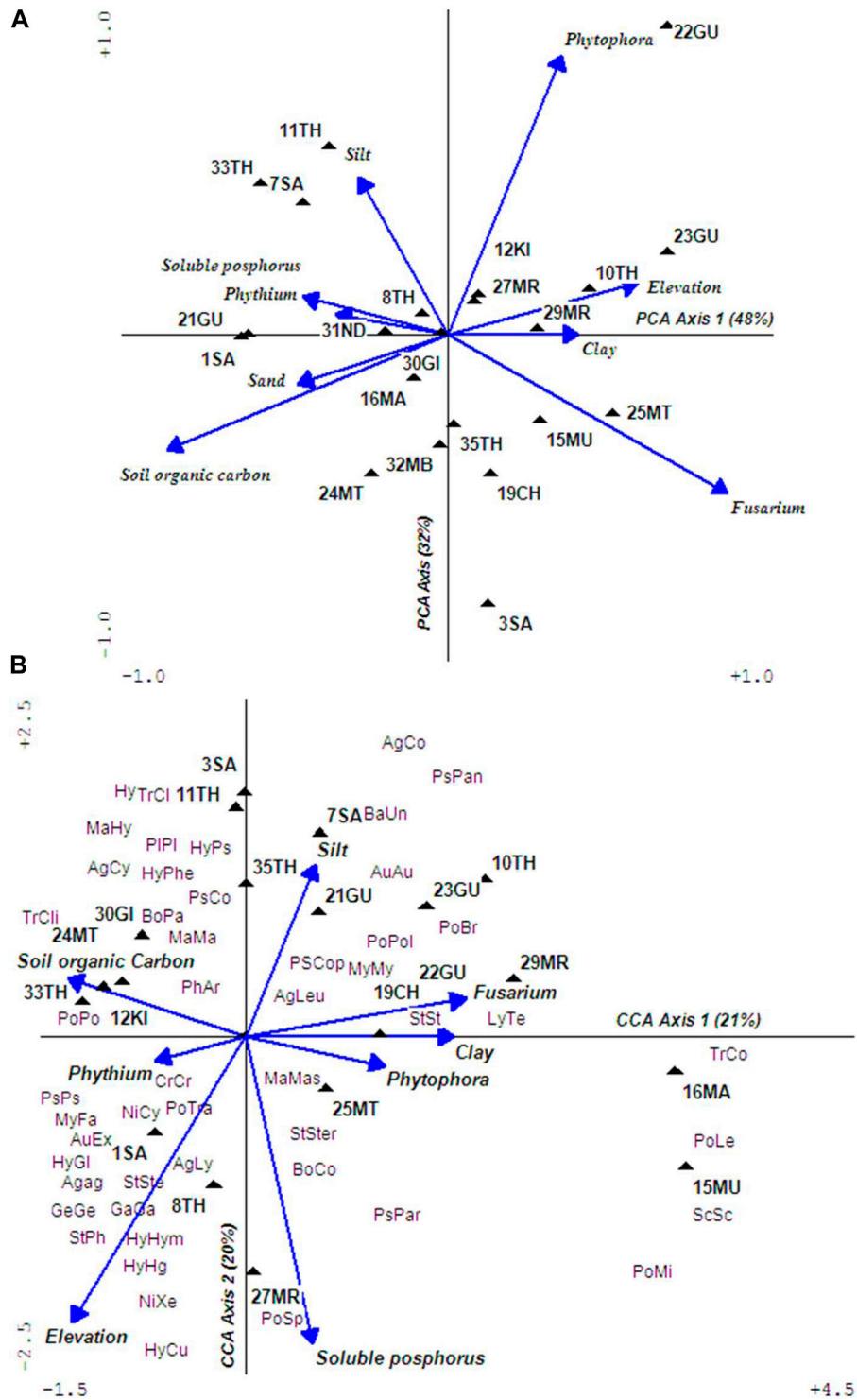
Sampling sites	Site name	Water quality	Soil parameters	Macroinvertebrates	Diatoms	Fish	Herpetofauna	Vegetation	Macrofungi	Birds
1SA	Sagana hatchery	1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2	–
2SA	Sagana KFS	1–2	–	1–2	1–2	1–2	–	1–2	–	–
3SA	Sagana mid	5–6	–	6	4–6	5–6	5–6	–	–	–
4SA	Sagana lower	5–6	–	6	5–6	5–6	5–6	4–6	–	–
5SA	Sagana/Thegu	5–6	–	–	4–6	–	–	–	–	–
6SA	Sagana/Thegu/ Nairobi 1	5–6	–	–	4–6	–	–	–	–	–
7SA	Sagana/Thegu/ Nairobi 2	5–6	3–4	6	4–6	5–6	5–6	4–6	4–5	–
8TH	Thegu upper	2–3	1–3	1–2	3–4	1–2	–	2–3	1–2	1–2
9TH	Thegu mid 1	4–5	–	–	4–5	–	–	–	–	–
10TH	Thegu mid 2	5–6	4–6	6	5–6	5–6	5–6	–	3–5	–
11TH	Thegu lower	5–6	4–5	6	5–6	5–6	5–6	–	3–5	–
12KI	Kimahuri	4–5	4–5	–	4–5	–	–	4–6	3–4	–
13NA	Nairobi	5–6	–	6	4–5	5–6	5–6	–	–	–
14AH	Amboni/Honi	4–5	–	4	4–5	4	–	–	–	–
15MU	Muringato	4–5	4–5	–	4–5	–	–	–	5	–
16MA	Muringato/Amboni	4–5	3–4	4	4–5	4–5	–	–	5	–
17ZA	Zaina	1–2	–	–	1–2	–	–	–	–	–
18CH	Chania upper	2–3	–	3	2–3	1–2	–	–	–	–
19CH	Chania mid	3–4	3–4	4	3–4	3–4	–	–	3–4	–
20CH	Chania lower	4–5	–	–	4–5	3–4	–	–	3–4	–
21GU	Gura upper	1–2	1–2	1–2	1–2	1–2	1–2	1–2	2–4	1–2
22GU	Gura mid	2–3	3–5	3	3–4	3–4	3–4	3–4	2–4	3–4
23GU	Gura lower	3–4	3–5	4	4–5	3–4	3–4	3–4	2–4	3–4
24MT	Mathioya upper	1–2	2–4	1–2	1–2	1–2	–	1–2	2–3	–
25MT	Mathioya mid	3–4	4–5	3	3–4	3–4	3–4	–	3–4	–
26MT	Mathioya lower	4–5	–	–	4–5	3–4	–	–	–	–
27MR	Maragua upper	1–2	2–4	1–2	1–2	1–2	1–2	1–2	2–4	–
28MR	Maragua mid	3–4	–	–	3–4	3–4	3–4	–	–	–
29MR	Maragua lower	4–5	4–5	5	5–6	3–4	–	4–5	3–5	–
30GI	Githambara	4–5	3–4	–	4–5	–	–	3–4	2–4	3–4
31ND	Ndiara	2–3	2–3	1–2	2–3	1–2	1–2	3–4	–	3–4
32MB	Mbuguti	2–3	–	3	2–3	3	–	3–4	–	3–4
33TH	Thika upper	1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2	1–2
34TH	Thika mid	4–5	–	4	3–4	4	–	–	–	–
35TH	Thika lower	4–5	4–5	4	5–6	3–4	3–4	5–6	4–5	–
36CT	Chania (Thika) lower	4–5	4–5	–	5–6	3–4	–	5–6	4–5	–

distribution seemed to be influenced by both micro- and macroenvironmental factors relating to habitats (**Figure 9B**). The undisturbed sites supported *Agaricus*, *Cuphophyllus*, *Hygrocybe*, *Hygrophorus*, and *Marasmius*, while moderately impacted areas had higher abundances of ectomycorrhiza species of *Laccaria* spp. It was evident that macrofungi abundances and diversity decreased downstream as a response to decreasing SOC. The majority of macrofungi community recorded in UTR were saprophytic (90%), colonizing dead wood, litter, and soil organic matter.

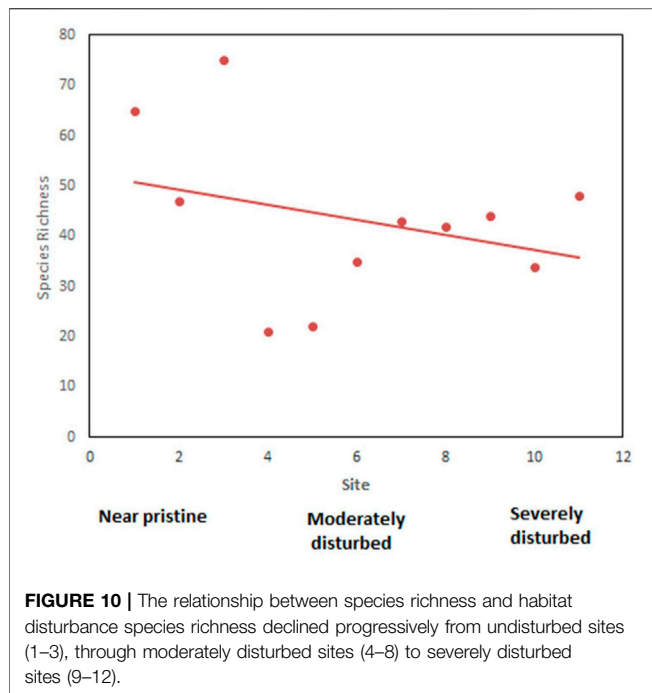
## Birds

Birds were studied at 10 sites and richness was highest in tier 2 sites, gradually declining across the moderately disturbed sites (tiers 3 and 4) to the lowest in tiers 5 and 6 sites (**Figure 10**). Kenrick's starling, *Poeoptera kenricki*, a regional endemic (Kenya and Tanzania) bird was recorded in the undisturbed forest sites (tiers 1 and 2). However, two local endemics Hinde's babbler, *Turdoides hindei*, and Hunter's cisticola, *Cisticola*

*hunteri*, were recorded at tiers 3, 4, 5, and 6 sites. Species occurrence indices were not significantly higher at tiers 1 and 2 sites than at the other sites (tier 2 index = 5.95; tiers 3 and 4 index = 5.87; tiers 5 and 6 index = 5.16,  $p > 0.05$ ). Severely modified sites (tiers 5 and 6) had the lowest average occurrence indices. Yellow-whiskered greenbul, *Eurillas latirostris* (forest generalist F), gray apalis, *Apalis cinerea* (a true forest specialist FF), and tropical boubou (a forest visitor f) were the most commonly encountered species at tier 2 sites, while at tiers 5 and 6 site, yellow-whiskered greenbul (F), gray-backed Camaroptera, *Camroptera brachyura* (f), and common bulbul, *Pyconotus barbatus* (f) were the most common. Baglafaecht weaver, *Ploceus baglafaecht*, red-eyed dove, *Streptopelia semitorquata*, and northern fiscal, *Lanius humeralis*, all forest visitors (f) were the most common in the severely modified sites. Predictably, the diversity of forest specialist species was higher in the tier 2 sites and completely absent in sites in tiers 3 to 6 (**Figure 11**). Conversely, the diversity of forest visitor species was highest in tiers 5 and 6 sites.



**FIGURE 9 |** Ordination plots of PCA (A) and CCA (B) showing ordination of sites according to environmental variables and species compositions in the UTR watershed. The abbreviated four-letter labels signify macrofungi with the first two uppercase letters standing for family and the next two lowercase letters genus. Full taxon names are provided as **Supplementary Table S4**. Soil parameters used to prepare PCA are provided as **Supplementary Table S5**.

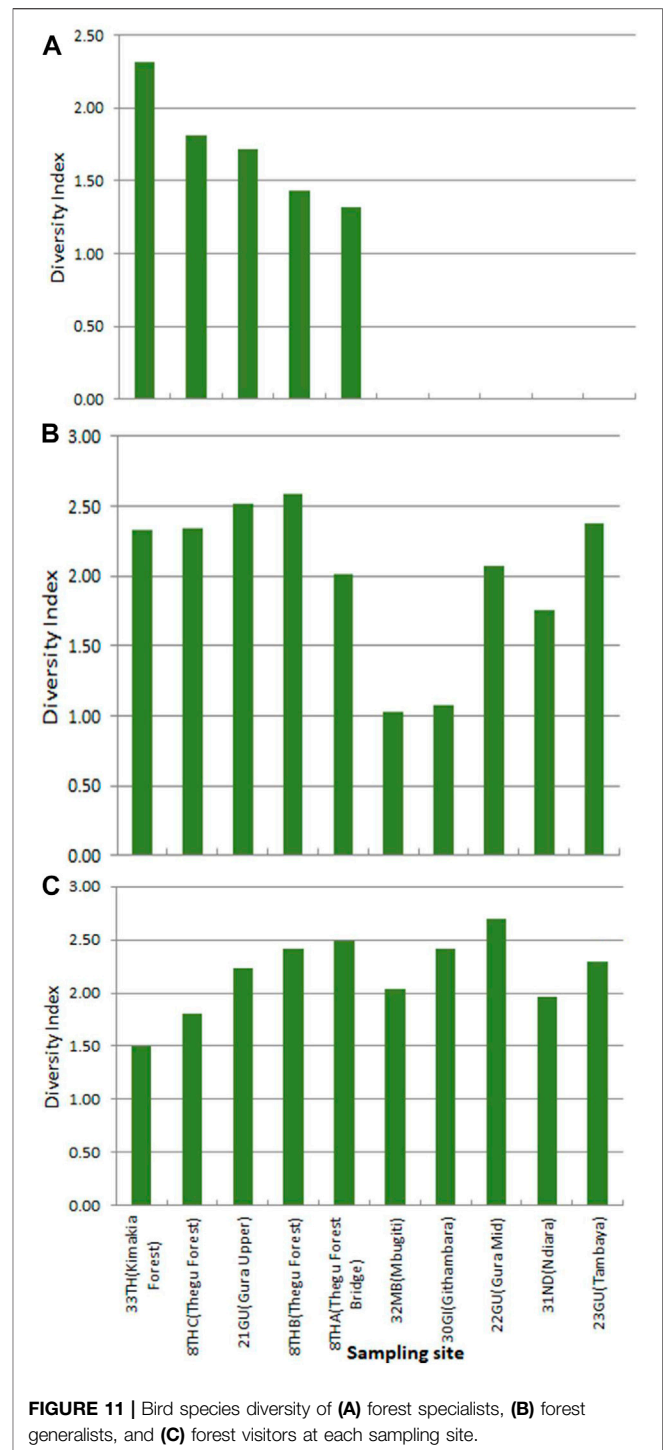


### Characterization of Sampled Sites into BCG Tiers

All data collected during this study were individually used to assign all 36 permanent sampled sites to various BCG tiers (Table 1). As predicted sites in undisturbed areas represented ecological conditions in tiers 1 and 2, moderately disturbed (tiers 3 and 4), and severely human-impacted areas were classified as tiers 5 and 6. The taxonomic groups were found to complement each other with each taxonomic group assessing ecological conditions of their habitats to a certain degree correctly. The use of multivariate analysis and examinations of taxa abundance and distributions assisted in the identification and selection of biological components (taxa), water, and soil quality parameters that were indicators of varying levels of landscape conditions. As predicted, ecological conditions deteriorated downstream in response to agricultural intensification.

### DISCUSSION

As predicted, analyses of water and soil parameter as well as biological data from both terrestrial and aquatic habitats assisted in placing sampled sites into BCG tiers (Table 1). Measurements of water and soil parameters validated changes in ecological conditions and more specifically the establishment of undisturbed reference sites. The decision to consider both terrestrial and aquatic taxa, followed by determination of their interactions with associated water or soil parameters assisted in identifying environmental stressors in UTR. More important was the identification of indicator species both in terrestrial and aquatic habitats that can be used



to monitor and assess ecological conditions by parataxonomists or ordinary citizens, and the results can be appreciated at all levels of expertise.

This study revealed that all the seven taxonomic groups responded significantly to ecological condition changes in the UTR watershed. Both natural and anthropogenic factors influenced taxa abundances and distributions. Elevation, a natural factor, was one of the factors that interacted

significantly with all taxonomic groups. Many of the undisturbed sites are found at higher elevation particularly in the headwaters draining protected lands. The elevation is also known to be a surrogate measure of temperature (McGuire et al., 2012). Global increments of temperatures are a consequence of climate change and land use driven by human activities such as impacts of land-cover changes that are found to be both intensive and widespread in parts of the watershed (Vitousek, 1994). Not surprisingly, land-use change was also found to affect water quality parameters in rivers such as conductivity, turbidity, and discharge. Land-cover change in watersheds of Rivers Thegu, Sagana, and Nairobi is suspected to be the major contributor of low water flow as well as increasing temperature. Also, uncontrolled water abstraction for irrigation agriculture contributes to high conductivity levels that are found to adversely affect most aquatic taxonomic groups. The high turbidity levels in mid to lower sections of rivers are also attributed to land-use cover changes and improper farming practices.

The overall goal of this study was to understand watershed degradation in UTR in order to restore and sustain its capacity to support and provide ecosystem services of water and biodiversity conservation (MEMR 2012). Specifically, the initiative was aimed at laying down a strong foundation for the establishment of a bioassessment framework to support rehabilitation of the UTR watershed under the auspices of the Upper Tana Nairobi Water Fund (UTNWF) initiative. A primary motivation for this study was to develop bioassessment tools that could reliably track condition and change attributable to activities of the NWF in a way that could be easily understood, communicate to the UTNWF and their cooperating partners, government agencies, academic institutions and the affected communities in the watershed, each of which has varying knowledge and expertise in interpreting biological condition. One of the major impediments to the implementation of successful rehabilitation activities is the lack of an official and structured biomonitoring network to gather and evaluate ecological data. A recent global analysis of the ecological conditions of rivers observed that most of them have poor waters, a situation attributed to lack of monitoring programs due to economic constraints, technical limitations, and limited knowledge of abiotic and biotic components, as well as poor awareness by decision makers (Feio et al., 2021). Also, insufficient citizen understanding and involvement contribute to reduced success and sustainability of rehabilitation initiatives.

The approach by UTNWF and NMK to develop a pilot BCG framework for a comprehensive bioassessment of rivers in the UTR watershed using seven taxonomic groups yielded promising results. The BCG assessment utilities were modified to accommodate terrestrial taxonomic groups, including vegetation, macrofungi, herpetofauna, and birds, which allow better incorporation of the river to the basin to ecological network biomonitoring. This approach has been generally ignored in the overall rehabilitation of rivers. There must be a long-term and extensive monitoring approach that considers ecological health that includes the suite of ecological components in watersheds or catchments (Buss et al., 2015). Many of the terrestrial biological components used to describe ecological conditions that have been

used elsewhere including the use of bird feeding guilds, abundance, and distribution to indicate various forest conditions (Furness and Greenwood 1993; Bennun et al., 1996; Bryce et al., 2002), how vegetation is important in supporting ecological processes and functions in landscapes (Handa et al., 2012; Riis et al., 2020), the strong interactions that exist between macrofungi and their environments (Mangan et al., 2010; Segnitz et al., 2020), and herpetofauna are very sensitive sentinels of environmental change due to their permeable thin skin and complex life cycle that makes them vulnerable to chemical and physical changes in both terrestrial and aquatic habitats (Bell and Donnelly, 2006). A program with several biomonitoring taxa is likely to bring on board many stakeholders and in doing so, assist in overcoming challenges that bewilder biomonitoring programs such as poor knowledge of biodiversity especially in developing countries, as well as increasing public awareness on the importance of river ecosystems and ecosystems services as such the need for motivating landscapes rehabilitation projects (Leigh et al., 2019). These taxa are widespread and relatively well-known locally and so easy to popularize among the residents for monitoring.

As expected, the aquatic taxonomic groups of macroinvertebrates, diatoms, and fish grouped sampled sites into various tiers consistently and similarly to those of terrestrial taxa. The response of macroinvertebrates to water quality was consistent with other studies carried in Kenya (Cumberlidge, 1981; Mathooko and Mavuti, 1992; Mathooko, 2002; Dobson et al., 2002; Mwaaura et al., 2002; Smart et al., 2002; Ndaruga et al., 2004; Muli, 2005; Kibichi et al., 2007; Kundu et al., 2017; Ochieng et al., 2019; Raburu et al., 2009; Masese et al., 2009; Masese et al., 2012; Nyakeya et al., 2009; Aura et al., 2010, 2017; Ojunga et al., 2010; Raburu and Masese, 2012; Minaya et al., 2013; Ngodhe et al., 2013; Kilonzo et al., 2014; Mbaka et al., 2014a; Mbaka et al., 2014b; M'Erimba et al., 2014b; Odhiambo and Mwangi 2014; Gichana et al., 2015, Orwa et al., 2015; Minoo et al., 2016; Kundu et al., 2017). The availability of this huge body of literature offers opportunities to strengthen the use of BCG, especially overcoming problems of determining undisturbed ecological conditions as well as the knowledge needed during pre- and post-status of ecosystems during rehabilitation programs. Only a few studies exist on fish bioassessment (Raburu and Masese, 2012; Achieng et al., 2021), and we recommend their continued promotion because they are sensitive to effects of poor agricultural practices and deforestation, which cause sedimentation and loss of habitat diversity and heterogeneity (Hocutt et al., 1994; Ganasan and Hughes, 1998; Toham and Teugels, 1999). Similarly, the use of diatoms in bioassessment of rivers is still at a nascent stage in Kenya (Ndiritu et al., 2006; Triest et al., 2012); however, findings of this study found them to be very reliable in assessing river conditions, especially the effects of climate on water quality.

The application of multivariate analyses of PCA, DCA, and CCA assisted in identifying water quality parameters adversely compromised as well as grouped sampling sites according to their taxa similarities. Moreover, the analyses ordinated taxa and sampling sites along an elevation-environment stress gradient that assisted in identifying and placing all 36 permanent sampling

sites in any of the six BCG tiers (**Table 1**). Agboola et al. (2020) employed a multivariate approach in the selection and validation of reference condition in monitoring and management in South Africa. By using the BCG, it was possible to prioritize sites requiring rehabilitation in the UTR watershed, nature of restoration, and to achieve specific ecological conditions. For instance, rivers draining dry sub-catchments of Thegu, Nairobi, Sagana, Honi, and Amboni were experiencing low water flow discharges during dry seasons which caused elevated levels of conductivity, consequently causing stress on aquatic taxa. Those rivers draining the Aberdare watershed were primarily affected by improper land-use practices that affected discharges and turbidity.

Going forward, there is an urgent need for countries to establish national bioassessment frameworks to increase the body of knowledge to support river rehabilitation programs. Rivers are major sources of water, and their protection is crucial if countries are to meet United Nations Sustainable Development Goals' targets that depend on secured water future. Just like in other parts of the world, river monitoring initiatives in Kenya are limited by 1) coordination across institutions and between stakeholders, 2) scientific gaps, and 3) insufficient resources (Feio et al., 2021). The current attempts by UTRNWF in the UTR to have bioassessment to support rehabilitation programs is laudable and should extend to other major watersheds (Crafter et al., 1992; MEMR 2012). The UTR watershed with an area of 8,340 km<sup>2</sup> is experiencing environmental degradation due to poor land and water management practices, and the consequences are reduced surface water qualities and quantities resulting in environmental crises that now threaten the social, political, and economic systems in the region (WRMA Water Resources Management Authority, 2014). Crucially, this watershed is a major source of water for domestic, agricultural, and industrial sectors for a human population of 4.87 million in UTR and another 95% of 4.4 million people living in Nairobi City (County). Also, waters from UTR generate 60% of hydropower energy used in Kenya, with sedimentation being a major concern on the longevity of dams.

## CONCLUSION

The development of BCG models using multiple taxa groups as a bioassessment framework helped describe ecological conditions in rivers and landscapes (watersheds) in UTR. The initial BCG metrics were developed based on aquatic taxonomic groups of fish, macroinvertebrates, and diatoms to support the objectives of restoring and maintaining the chemical, physical, and biological integrity of the USA's water resources (Clean Water Act; CWA, 1972). However, it was discovered during this exercise that there was a strong case that the BCG framework can also be applied in terrestrial ecosystems using associated taxa such as birds, amphibians, macrofungi, and vegetation. The strong relationship between landscape and aquatic ecosystems demonstrated through this study informs this idea (Buss et al., 2015). Analyses of the relationship between all the seven taxonomic groups and environmental variables using analytical techniques of

multivariate, species abundance, and distribution measures of richness, diversities and indicator species assisted in the grouping of 36 sites according to six BCG tiers. Indeed, the seven taxonomic groups complemented each other, with each taxonomic group reliably assessing the ecological conditions of each site. In building different BCG models, it was possible to identify taxa indicating various ecological conditions that in the long term can be proposed as indicator flagship taxa in the UTR. In most cases, flagship taxa are known by local communities and citizens and this makes it easier for them to contribute to data collection and bioassessment programs, which is one way to promote public or citizens' environmental awareness, education, and participation (Graham et al., 2004; Leigh et al., 2019). The aim is to strengthen this long-term biomonitoring program as well as make it compatible with other taxa assessment programs such as national mapping of birds under the Kenya Bird Map (<http://www.birdmap.africa/coverage/country/Kenya/>; Wachira et al., 2015). In summary, the capacity of the BCG models to assess landscape conditions meant that they can be used to identify important habitats for conservation, direct investment for restoration, and track progress using measurable biological and environmental parameters targets under a long-term biomonitoring program.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

## ETHICS STATEMENT

The research and findings presented in this manuscript were obtained under auspices of National Museums of Kenya (NMK) which is governed by its collection and research policy framework that abides by national and international research standards and mandated by an Act of Parliament, The National Museums and Heritage Act of 2006 (<https://www.museums.or.ke/biodiversity-database/>). Thus, NMK is a Kenyan government institution and its core mandate is to undertake biodiversity research and manage all biological collections in Kenya.

## AUTHOR CONTRIBUTIONS

GN conceived the manuscript with TT, PN, and DC and then supervised the study and contributed valuable comments. GN, TT, PN, VM, EN, GK, LN, PK, PM, MM, JG, and DO collected data. All authors contributed to the article and approved the submitted version.

## FUNDING

This study was made possible through support provided by the International Fund for Agricultural Development (IFAD)-GEF



6<sup>th</sup> framework through the Nature Conservancy (TNC)-Upper Tana Nairobi Water Fund (NWF) initiative, under the terms of subaward Agreement ID. No. 270317 (TNC -project ID No. P104186, award ID No. A103672). The content and opinions expressed herein are those of the author(s) and do not necessarily reflect the position or the policy of such agency or The Nature Conservancy, and no official endorsement should be inferred.

## ACKNOWLEDGMENTS

The project was implemented by the National Museums of Kenya (NMK), Centre for Biodiversity under the directorship of

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Mzalendo Kibunjia and coordinated by TT. We wish to thank local communities in Nyeri and Murang'a for their warm welcome during the study period. We are grateful to the TNC-NWF team led by George Njugi and Anthony Kariuki for introducing us to rehabilitation target sites in the Upper Tana River watershed.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.671051/full#supplementary-material>

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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