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Inventory and Ecological Characterization of Ichthyofauna of Nine Lakes in the Adamawa Region (Northern Cameroon, Central Africa)

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Abstract: The fish diversity of the Adamawa lakes is among the most undocumented in Northern Cameroon. Faced with this lack of knowledge, an inventory of ichthyofauna and habitats characterization was conducted in nine lakes. Seven lakes (Assom, Gegouba, Massote, Mbalang, Ngaoundaba, Piou and Tizong) are located in the Sanaga Basin and two (Bini and Dang) are located in the Lake Chad Basin. In order to assess the composition and variation in fish assemblage, eight sampling campaigns were carried out seasonally between 2017 and 2018; they revealed 26 species of fish distributed in 6 orders, 9 families and 16 genera. Communities in Lakes Assom (13 species) and Bini (9 species) were the most diverse. Omnivorous (42.3%) and spawners in open water or on substrates of sand, gravel, rock or plants (69.2%) were the most represented. Nonmetric multidimensional scaling, analysis of similarities (ANOSIM), and similarity percentage analysis (SIMPER) revealed that fish species composition differed significantly among lakes. Canonical correspondence analysis (CCA) identified temperature, pH, TDS, and conductivity as variables explaining the most variation in fish species. The presence of four endemic species in the Sanaga Basin in lakes Assom, Gegouba, Massote and Piou, shows that these lakes stand out as hotspots for conservation due to the uniqueness of their ichthyofauna.

Keywords: diversity; distribution; fish species; limnology; Ngaoundéré

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1. Introduction

Freshwater fish represent one-fourth of all vertebrate species, despite freshwater occupying less than 1% of the Earth's surface [1]. They are especially vulnerable to human alterations resulting from species introduction, overexploitation, fragmentation and degradation of continental watercourses, and climate change [2]. Freshwater vertebrates, especially fish, are currently the most threatened groups of vertebrates on our planet [3].

The conservation status and ecology of freshwater fish are less documented than terrestrial vertebrates due to biases in conservation research and management toward more charismatic species [1]. Research into ecological subjects, environmental necessities, and pressures of freshwater fish is crucial to develop effective management measures for freshwater ecosystems. Understanding these environmental features remains a key concern of freshwater fish conservation biology [4].

African lakes and lagoons are increasingly experiencing overexploitation of their fish resources due to commercial fisheries, overfishing, and increasing population [5,6]. This situation has brought about conservation measures and the rational management of stocks. Measures are based on the acquisition of accurate information regarding the ecology, the composition of ichthyological faunas, and their level of exploitation in the waterbodies [6]. In Cameroon, at least 39 lakes have been identified along the Cameroon Volcanic Line (CVL), arranged into three large groups: the southwestern lakes (12), the northwestern lakes (19), and the Adamawa (8) [7].

In the southwest region, lakes Barombi Mbo (4°39′43.2′′ N, 9°24′38′′ E, Alt. 301 m), Bermin (05°09′36′′ N, 09°38′11′′ E, Alt. 475 m) and Ejagham (5°45′15.3′′ N, 08°59′05′′ E, Alt. 131 m), located at low altitude (<500 m), are best known for their species flocks of cichlid fish. The most diverse and famous, the crater lake, Lake Barombi Mbo (with approximately 415 ha, maximum depth of 110 m and presence of an outlet named "Kumba River" [7,8]) is inhabited by fifteen fish species, twelve of which are endemic, and except for the clariid catfish (*Clarias maclareni* (Trewavas, 1962)), all endemics are tilapiine cichlid fishes [8,9]. The eleven endemic cichlid species probably arose in situ following a colonization event no earlier than 1 million years ago [10–13]. During this time frame, the species have diversified with respect to ecology, as documented by their trophic niche specialization [14,15], as well as with respect to their water depth preference [16] and repeated gene flow between radiations and neighboring riverine populations, including allopatric and sympatric phases after initial colonization [9,17–21]. While nine out of the eleven Barombi Mbo cichlid species are commonly and syntopically found in the shallow littoral zone of the crater lake, two species have colonized the deep-water zone: *Konia dikume* (Trewavas, 1972), an obligatory deep-water specialist that inhabits the zone at around 20 m depth [16], and *Myaka myaka* (Trewavas, 1972), a seasonal deep-water species that occurs in the deep-water habitat during the dry season (November–April), yet migrates into the shallow littoral zone for spawning during the peak of the rainy season (June–August) [13,16]. The Barombi Mbo is under immediate threat; it has been registered as a Ramsar site, numbered 1643, since 2006 [22], and was retained as a Key Biodiversity Area (KBA) in 2021 [23]. The social and cultural life of the Barombi Mbo people is intimately linked to the use of the resources of the lake through fishing, mythology and transport, and to the surrounding land through farming. It is also a source of clean water for the metropolis of Kumba and its environs. Overfishing, introduction of exotic fish to the ecosystem, pesticide spraying of cocoa trees within the catchment area, and deforestation of the crater rim are the main (potential and actual) threats to the site, for which the elaboration and implementation of a management plan needs to occur [9,22]. The crater lake, Lake Bermin (with approximatively 60 ha of surface, maximum depth of 14.5 m and presence of an outlet which drains its waters into the "Mbu River" [7,8]), is inhabited by a radiation of nine *Coptodon* endemic species founded by the distantly related riverine species *Coptodon guineensis* (Günther, 1862) [21]. Lake Ejagham (a solution basin produced by groundwater dissolving carbonates out of the marine sediments that are supposed to underlie the lake [21], or a bolide impact [24], not a crater lake [24], with approximatively 70 ha of surface, maximum depth of 17 m and presence of an outlet named "Amarafú" [7,8,21]) also hosts a radiation of three *Coptodon* endemic species (*Coptodon fusiforme* (Dunz and Schliewen, 2010), *C. deckerti* (Thys van den Audenaerde, 1967), *C. ejagham* (Dunz and Schliewen, 2010); there is a fourth described species, *C. nigrans*, unsupported by genetic structure [19]) and a pair of *Sarotherodon* (*S. knauerae* Neumann, Stiassny and Schliewen, 2011 and *S. lamprechti* Neumann, Stiassny and Schliewen, 2011; formerly *S.* sp. "mudfeeder"/*S.* sp. "bighead" [23,25]) founded, respectively, by the distantly related riverine species *C. guineensis* and *S. galilaeus* (Linnaeus, 1758). Threats already described in Barombi Mbo also largely apply to the two other lakes [9].

In the northwest region, lakes Nyos (6°26′0.00′′ N, 10°18′0.02′′ E, Alt. 1091 m) and Monoun (5°34′45′′ N, 10°35′15′′ E, Alt. 1080 m) are well known as "killer lakes" due to their accumulation of gases (CO_2) which sometimes release in the form of a lethal explosion [20]. The faunas of these "killer lakes" are poorly diversified, no species flock was found in these high-altitude (>1000 m) lakes probably due to their location not being favorable to gene flow between the lakes and neighboring riverine populations [8]. Water from Lake

Nyos (approximatively 158 ha of surface, maximum depth of 208 m [7]) is discharged over a natural weir (outlet) which has a free fall of 22.3 m [26]; although there are fish in the streams and rivers near Lake Nyos [26] such as cyprinids and cichlids (Bitja Nyom, pers.com), they have no direct access into the lake [26], but *Oreochromis noliticus* (Linnaeus, 1758) which currently breeds in the lake was probably introduced after the latest lake disaster (Bitja Nyom, pers.com). Lake Monoun (approximatively 53 ha of surface, mean depth of 96 m, and presence of an outlet and inlet [7,27]) registers at least two native species (*Enteromius bourdariei* (Pellegrin, 1928) and *Labeobarbus brevispinis* (Holly, 1927) [28]) and is a fishing ground for local villagers [29].

Meanwhile, the Adamawa lakes, located at high altitude (generally >1000 m) remain unknown, and their fish faunas have not yet been studied, with the exception of a recent study focused on the *Hemichromis camerounensis* populations from three lakes (Bini, Dang and Tizong) [30]. The current work aims to inventory the fish taxa that inhabit the Adamawa lakes and to characterize their habitat (physicochemical parameters of surface water, composition of trophic, and even, reproductive groups), in order to assess the composition and variation in fish assemblages.

2. Material and Methods

2.1. Study Sites

This study was carried out from 2017 to 2018, yearly from December to March for the dry season, and May to August for the wet season, in nine lakes. Two lakes (Bini and Dang) are located in the Bini River system (Lake Chad Basin) while seven (Assom, Gegouba, Massote, Mbalang, Ngaoundaba, Piou and Tizong) belong to the Djerem River system (Sanaga River Basin). All the lakes studied are located in the Adamawa region of Cameroon (Figure 1 and Table 1). Lake Assom, which was not listed previously by Kling [7], is a natural depression located about 45 km from the town of Tibati [31,32]; its diameter is 1 km in the north–south direction and 1.2 km in the east–west direction; it discharges its water by an outlet connected to the Djerem River [31]. It is characterized by savanna vegetation, fishing activities are practiced by approximatively ten fishermen, while pastoral activities are practiced there by an uncontrolled number of herdsmen; no agricultural activity was observed around this aquatic ecosystem during our visit. Lake Bini, with an undocumented origin, is probably a natural depression or a man-made lake; it discharges its water into the river Bini through an outlet [33]. It is characterized by savanna vegetation on its shores [34]. Heavy metals were found in the water [35]. On the banks of this lake, uncontrolled agricultural and pastoral activities are practiced. Lake Dang is documented as natural depression [36]; it discharges its water through an outlet into the Bini River [33]. It is eutrophic and characterized by vegetation similar to that of Lake Bini, although less dense, probably because of its proximity to a major national road which facilitates access to the site. Its water contains heavy metals originating from anthropic activities practiced around the lake [35]; its banks are used for agriculture, livestock pastoralism and washing [36]. Lake Gegouba is a crater lake with an outlet during periods of heavy rainfall; it is located about 25 km southeast of the town of Ngaoundéré [35]; according to [37], the watershed is occupied 60% by grasses, 35% by trees, and less than 1% by agricultural and pastoral activities, with rocky outcrops comprising the remaining 5%. Pastoral activities are practiced there by an uncontrolled number of herdsmen, while no fishermen were seen during our visit. Lake Massote is located in a valley surrounded by mountains [7]; although this lake is poorly documented, it appears as a natural depression with inlet and outlet channels which are functional only during the rainy season. During our visit, we noticed the practice of fishing by about 16 fishermen. Uncontrolled pastoral activities are practiced by herdsmen, and the savanna trees are poorly conserved. Lake Mbalang is a crater lake located 15 km from the town of Ngaoundéré; it is reported to have an outlet only during the rainy season [38]. The watershed is occupied 85% by grasses, 15% by trees, and less than 1% by agriculture, while rock outcrops account for less than 1% [37]. The lake edge is colonized by a very dense crown of aquatic plants; only two fishermen were observed during our visit. Lake Ngaoundaba is a crater lake located 20 km from Ngaoundéré [7]; the watershed is equally occupied by grasses and trees, agriculture and rock outcrops account for less than 1% [37], and sediments show low contamination by heavy metals [39]. We registered only one fisherman for this lake during our visit [7]. Lake Piou is not yet documented; it is probably a natural depression or a man-made lake with an outlet. The savanna's trees around the lake are well-conserved. Fishing activities are practiced by only one fisherman, who was seen during our visit. Lake Tizong is an endorheic crater lake located in Mount Mardja and embedded in a 70 m crater [33]; the watershed is occupied 40% by grasses, 60% by trees and less than 1% agriculture, while rock outcrops represent less than 1% [37]. During our fieldwork, we registered the presence of only one fisherman.

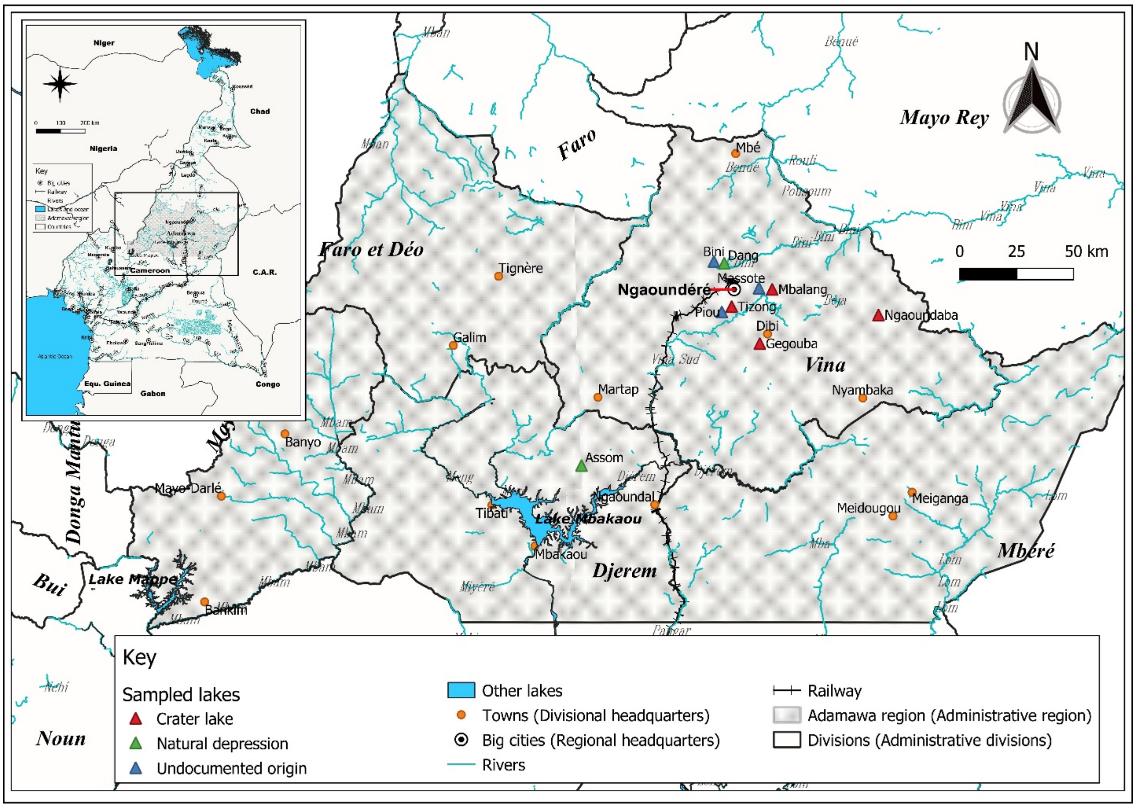

Figure 1. Geographical location of the study sites.

Table 1. Synthetic geographical data on study lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong). Zm = maximum depth; Z = minimum depth; (*) = crater lake [7]; (**) = natural depression [31,36]; (***) = undocumented origin, probably a natural depression or a man-made lake.

Lakes	Latitude (°N)	Longitude (°E)	Altitude (m)	Surface (ha)	Zm (m)	Z (m)	Hydrographic System
Bi ***	07°25′54.01″	13°30′26.63″	1076	20 [7]	/	/	Lake Chad Basin [33]
Da **	07°25′29.01″	13°32′54.01″	1072	80 [7]	/	2.5 [34]	Lake Chad Basin [33]
As **	06°37′22.36″	12°58′56.51″	898	/	3–4 [32]	/	Sanaga Basin [32]
Ge *	07°06′23.14″	13°41′23.9″	1181	20 [7]	104 [7]	/	Sanaga Basin [33]
Ma ***	07°19′35.5″	13°41′10.8″	1073	5 [7]	/	/	Sanaga Basin [33]
Mb *	07°19′17.53″	13°44′18.73″	1110	50 [7]	52 [7]	/	Sanaga Basin [33]
Ng *	07°13′11.57″	13°69′37.01″	1178	10 [7]	62 [7]	/	Sanaga Basin [33]
Pi ***	07°13′53.7″	13°32′19.7″	1185	/	/	/	Sanaga Basin [33]
Ti *	07°15′11.00″	13°34′40.6″	1065	8 [7]	48 [7]	26.2 [7]	Sanaga Basin [32]

2.2. Data Collection

2.2.1. Measurement of Environmental Variables

The physicochemical parameters of the surface water (temperature, pH, total dissolved solids or TDS, and conductivity) were measured in situ at four points in each lake including the shore and offshore areas, using a HANNA HI 98129 multiparameter, while transparency was obtained using a Secchi disc, and the averages were considered for each parameter.

2.2.2. Capture and Storage of Fish Samples

From 2017 to 2018, fish were caught during eight sampling campaigns (twice in the dry season, December and March, and twice in the rainy season, May and August, yearly); we used a set of eight gillnets each measuring 10 m long and 2 m depth, with variable mesh sizes, respectively, of 10, 12, 15, 20, 25, 30, 35 and 40 mm. These different meshes reduced the selectivity of the gillnets [21]. In addition, the use of three traditional fish traps and a seine net 30 m long and 5 mm mesh size, made it possible to complete the qualitative sampling at each station. Gillnets and traps were set in the evening between 5 p.m. and 6 p.m., then visited the next morning between 6 a.m. and 9 a.m., and finally raised in the evening at 6 p.m., while the seine net was actively used in the shore zones during our presence in the field. This method allowed 24 h per day fishing to be carried out per lake per campaign using gill nets and traditional traps, and a couple of hours of fishing using seine nets [40]. Captured fish specimens were photographed using a Nikon camera, and weighed to the nearest gram using an electronic scale Denver instrument®. Specimen standard length and total length were measured to the nearest millimeter using an ichthyometer [28]. Afterwards, fish specimens were labeled and placed into cans containing 10% formalin [41], which were brought back to the laboratory, then identified using the identification keys for West Africa including the Chad basin [42], and for lower Guinea including the Sanaga Basin [28].

2.3. Data Analysis

The analysis of variance (ANOVA) followed by the Tukey test allowed comparison of the physicochemical parameters of water between seasons. The ichthyological community samples were characterized using different ecological indices, namely, the Margalef species richness index (d), the Shannon–Weaver index (H′), and the Pielou equitability index (J). Margalef's index measured fish species richness in each site. It was calculated as $d = S - 1/\log N$, where S and N represent the number of species in a given sample and the total number of fish individuals in the stand, respectively [43]. The Shannon–Weaver index or diversity index was calculated as $H' = -\Sigma\, p_i \log 2\, p_i$, where $p_i = n_i/N$, and n_i corresponds to the number of individuals of species i [44]. The Pielou equitability index was calculated by the following formula: $J = H'/\log 2S$ [43].

Hierarchical cluster analysis (or hierarchical clustering) was performed to determine similarities between the lakes based on their physicochemical parameters [45,46]; this analysis sought to identify groups of lakes that may be similar in their species composition.

Fish species compositions were compared among lakes using nonmetric multidimensional scaling (NMDS) and analysis of similarities (ANOSIM) [47]. Similarity percentage analysis (SIMPER) was used to identify the contribution of fish species to the average dissimilarity between lakes [48]. Fish abundance data from lakes and environmental variables were log (x + 1) transformed. To investigate the relationship between environmental variables and variation in fish species composition, canonical correspondence analysis (CCA) was applied to the species abundance data [49–51]. In a CCA biplot, the direction of environmental variables to fish species was useful to indicate its relationship with the species. Fish species plotted in the same direction from the origin as an environmental vector were positively correlated with the variable, and a species plotted in the opposite direction indicated a negative relationship [52]. A Monte Carlo test with 999 permutations was used to determine whether the variables significantly ($p < 0.05$) explained the variation in fish species composition, or not.

The feeding status and reproduction habitats of the sampled fish were determined at the generic or specific level from the literature, when available [53,54]. Each species was first categorized into one of the following trophic groups: herbivorous/detritivorous (HER), invertivorous (INV), omnivorous (OMV), or piscivorous (PIS) [55], and secondly into one of the following breeding groups: open water/substratum egg scatters including sand, gravels, rocks and plants (SUB), egg nesters in sand nests, plants or foam (NES), and mouthbrooder (MOU) [54,55]. The frequency (%) of each trophic or reproductive group was calculated per lake; it was the ratio between the number of species in a given group and the total number of species inventoried at that station, multiplied by 100 [55]. Diversity and multivariate analyses were performed with PAST 3 [56].

3. Results

3.1. Physicochemical Characteristics of the Waters of the Lakes Studied

The analysis of the data (Table 2) showed that, in most cases, temperature, hydrogen potential, total dissolved solids, conductivity and transparency varied between lakes, and in some cases, between the dry and the rainy seasons.

Table 2. Seasonal variations of the physicochemical parameters of the water in the lakes studied: average ± standard deviation. The lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong). The seasons (D = dry, W = wet).

Lakes	Parameters				
	T (°C)	**pH**	**TDS (ppm)**	**CON (µs/cm)**	**Secchi (m)**
As D	25.95 ± 0.34 a	8.26 ± 0.18 a	8.6 ± 0.1 d	14.5 ± 0.12 jk	1.15 ± 0.09 g
As W	26.1 ± 0.11 a	5.98 ± 0.08 f	8.11 ± 0.02 d	12.17 ± 0.21 k	0.7± 0.02 ij
Da D	22.2 ± 0.5 f	5.18 ±1.10 g	14.89 ±1.41 d	24.96± 0.78 fg	0.45 ±0.02 kl
Da W	23.74 ± 0.08 de	5.06 ± 0.05 gh	19.84 ± 1.14 d	27.34 ± 1.75 f	0.35 ± 0.01 l
Bi D	23.55 ± 0.4 e	5.13 ± 0.05 gh	10.27 ± 0.28 d	17.32 ± 0.3 ij	0.55 ± 0.01 jk
Bi W	24.59 ± 0.07 cd	4.76 ± 0.06 h	12.47 ± 0.76 d	17.9 ± 1.24 hij	0.4 ± 0.0 kl
Ge D	25.75 ± 0.09 ab	7.25 ± 0.02 cd	121.15 ± 0.23 b	171.43 ± 0.09 c	6.25 ± 0.06 a
Ge W	25.82 ± 0.1 a	7.20 ± 0.03 cd	120.12 ± 0.5 b	169.62 ± 0.32 cd	5.32 ± 0.04 b
Ma D	25.35 ± 0.19 abc	7.52 ± 0.02 bc	14.31 ± 0.17 d	22.512 ± 0.14 gh	1.01 ± 0.03 gh
Ma W	25.4 ± 0.1 abc	8.56 ± 0.01 a	14.8± 0.2 d	21.8 ± 0.2 ghi	0.78 ± 0.02 i
Mb D	24.7 ± 0.01 c	6.73 ± 0.05 e	67.83 ± 12.88 c	165.36 ± 0.1 d	3.73 ± 0.06 e
Mb W	25.38 ± 0.06 abc	7.20 ± 0.02 cd	114.45 ± 1.35 b	157.65 ± 0.89 e	3.33 ± 0.03 f
Ng D	24.78 ± 0.12 bc	7.27 ± 0.02 bcd	121.71 ± 0.54 b	170.45 ± 0.47 c	4.5 ± 0.0 c
Ng W	26 ± 0.07 a	7.247 ± 0.02 cd	121 ± 0.57 b	169.05 ± 0.15 cd	3.35 ± 0.03 f
Pi D	25.49 ± 0.19 abc	7.63 ± 0.01 bc	8.41 ± 0.05 d	17.75 ± 0.11 hij	0.87 ± 0.02 hi
Pi W	25.8 ± 0.1 a	7.60 ± 0.24 bc	11.31± d	18.4 ± 0.88 hij	0.73 ± 0.01 ij
Ti D	22.08 ± 0.3 f	7.747 ± 0.17 b	165.05 ± 5.34 a	273.5 ± 2.82 a	4.18 ± 0.03 d
Ti W	25.73 ± 0.11 ab	6.97 ± 0.04 de	181 ± 0.18 a	256.475 ± 0.16 b	3.38 ± 0.04 f
F	41.92	158.83	337.8	9068.25	1992.41
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Values assigned with different letters in a given column are statistically different from the 5% threshold.

The temperature was relatively higher during the rainy warm season in all lakes, while significant variations ($p < 0.05$) between seasons were recorded in lakes Dang, Bini, Ngaounda, and Tizong. The highest value was recorded during the rainy season in Lake Assom (26.1 ± 0.11 °C), and the lowest during the cold dry season in Lake Tizong (22.08 ± 0.3 °C).

The pH values showed no significant variations between seasons in lakes Dang, Bini, Gegouba, Ngaoundaba and Piou. The low pH value in Lake Assom in the rainy season compared with the dry season was remarkable; such differences were also observed in lakes Tizong and Massote, but were less significant. Highest and lowest pH values were recorded during the rainy season in Lake Massote (8.56 ± 0.01) and during the dry season in Lake Bini (4.76 ± 0.06), respectively.

TDS values varied significantly between the dry and wet seasons only in Lake Mbalang. The highest and lowest values were recorded, respectively, in the wet season in Lake Tizong (181 ± 0.18 ppm) and in Lake Assom (8.41 ± 0.05 ppm).

No significant differences between seasons were noticed for conductivity in almost all lakes, except in Tizong and Mbalang lakes. Highest and lowest values were recorded, respectively, during the dry season in Lake Tizong (273.5 ± 2.82 µs/cm) and during the wet season in Lake Assom (12.17 ± 0.21 µs/cm).

Finally, the water transparency values were significantly different between seasons, except in Bini, Dang and Piou lakes; they were always higher in the dry season. All crater lakes (Gegouba, Mbalang, Ngaoundaba and Tizong) showed higher transparency values (above 3 m) than natural or man-made lakes (below 2 m). The highest and lowest values were recorded in the dry season in Lake Gegouba (6.25 ± 0.06 m) and in Lake Dang in the wet season (0.35 ± 0.01 m), respectively.

3.2. Relation between Lakes Based on Physicochemical Parameters

Based on physicochemical parameters, the hierarchical cluster analysis showed three groups of lakes. Group one (G1) was comprised of lakes Dang, Bini and Massote. These lakes had in common the lowest pH, conductivity, TDS and depth values. The second group (G2) was comprised of lakes Assom and Piou, and was characterized by intermediate values of pH, conductivity, TDS and depth. The third group (G3) consisted of lakes Ngaoundaba, Gegouba, Tizong and Mbalang, with the highest physicochemical parameters (Figure 2).

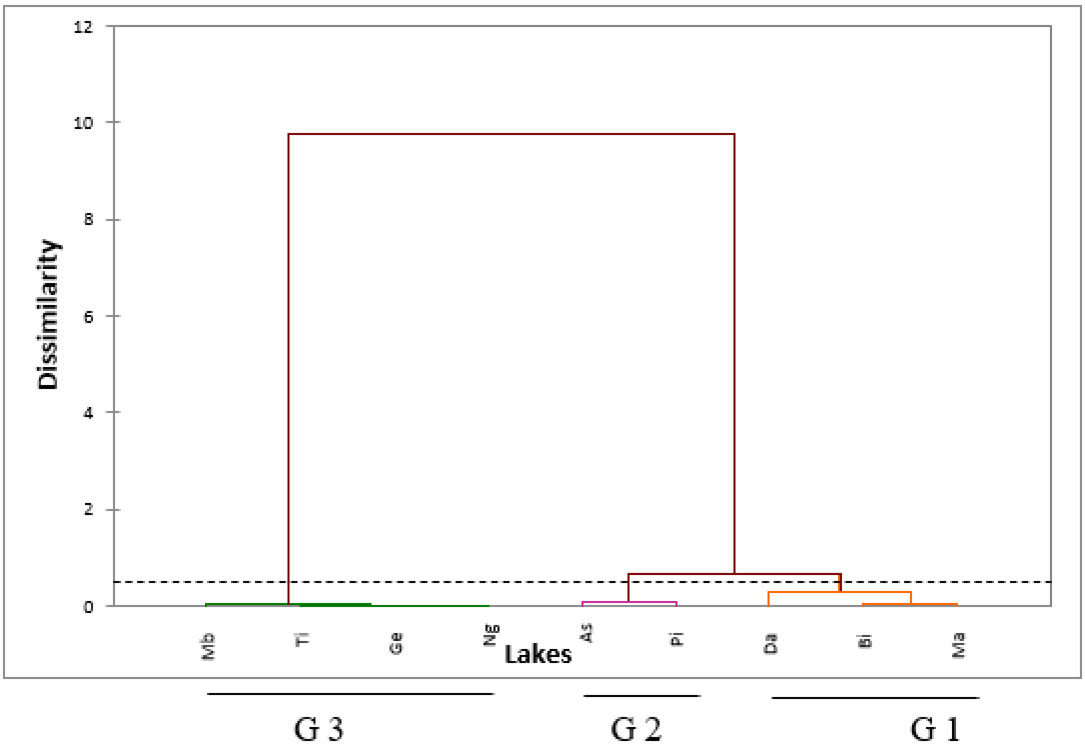

Figure 2. Cluster analysis showing dissimilarities between lakes based on physicochemical parameters; (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong).

3.3. Abundance of Taxa

During the current study of eight sampling campaigns, a total of 8395 fish specimens were collected, of which 26 fish species were identified (Table 3). They ranged across

16 genera, 9 families and 6 orders. The Anabantiformes, Perciformes, Siluriformes and Osteoglossiformes contained two families each, while Cypriniformes and Cichliformes contained one family each. The most diverse families were Clariidae (seven species), Cichlidae and Mormyridae (five species each), Cyprinidae (four species), and finally, Mochokidae, Channidae, Annabantidae, Latidae, and Arapaimidae (one species each).

Table 3. Orders, families and fish species collected in the Adamawa lakes and their ecological characteristics. Biogeographical characteristics (BC: E = endemic, I = introduced, N = native non-endemic, X = missing or non-existent data); trophic group (TG: HER = herbivorous/detritivorous; INV = invertivorous; OMV = omnivorous; PIS = piscivorous); reproductive group (RG: MOU = mouthbrooder, NES = keepers of eggs in nests of scum, holes, sand or leaves, SUB = spawners in open areas or on substrates of sand, gravel, rocks or plants); International Union for the Conservation of Nature (IUCN) status (LC = least concern, DD = data deficient, NE = not evaluated); the lakes (As = Assom; Bi = Bini; Da = Dang; Ge = Gegouba; Ma = Massote; Mb = Mbalang; Ng = Ngaoundaba; Pi = Piou; Ti = Tizong); Distribution (presence = †).

Taxa		Ecological Features				Presence–Absence in the Station									
Orders Families	**Species**	**BC**	**TG**	**RG**	**IUCN**	**As**	**Bi**	**Da**	**Ge**	**Ma**	**Mb**	**Ng**	**Pi**	**Ti**	**Code**
Osteoglossiformes Mormyridae	*Petrocephalus similis* (Lavoué, 2011)	E	INV	SUB	NE	†									S01
	Marcusenius mento (Boulenger, 1890)	N	INV	NES	LC	†									S02
	Paramormyrops kingsleyae (Günther, 1896)	N	INV	NES	DD	†									S03
	Brevimyrus niger (Günther, 1866)	N	INV	SUB	LC		†								S04
	Brienomyrus brachyitius (Gill, 1862)	N	INV	SUB	LC	†									S05
Arapaimidae	*Heterotis niloticus* (Cuvier, 1829)	I	OMV	NES	LC		†	†				†			S06
Cypriniformes Cyprinidae	*Enteromius martorelli* (Roman, 1971)	N	OMV	SUB	LC	†				†					S07
	Enteromius sp. «mbalang»	N	OMV	SUB							†				S08
	Garra cf *ornata*	N	HER	SUB							†				S09
	Garra cf *dembeensis*	N	HER	SUB							†				S10
Anabantiformes Anabantidae	*Ctenopoma* sp.	N	INV	SUB			†	†							S11
Channidae	*Parachanna obscura* (Günther, 1861)	I	PIS	NES	LC		†	†							S12
Perciformes Latidae	*Lates niloticus* (Linnaeus, 1758)	I	PIS	SUB	LC				†			†			S13
Siluriformes Clariidae	*Clarias camerunensis* (Lönnberg, 1895)	N	OMV	SUB	LC	†		†					†		S14
	Clarias gariepinus (Burchell, 1822)	I	OMV	SUB	LC	†	†	†		†					S15
	Clarias jaensis (Boulenger, 1909)	N	OMV	SUB	LC	†	†								S16
	Clarias longior (Boulenger, 1907)	N	OMV	SUB	LC	†									S17
	Clarias pachynema (Boulenger, 1903)	N	OMV	SUB	LC		†						†		S18
	Clarias sp. «mbalang»	N	OMV	SUB							†				S19
	Clarias sp. «massote»	N	OMV	SUB						†					S20
Mochokidae	*Synodontis rebeli* (Holly, 1926)	E	OMV	SUB	DD					†					S21
Cichliformes Cichlidae	*Oreochromis niloticus* (Linnaeus, 1758)	I	HER	MOU	LC	†	†	†	†	†		†	†	†	S22
	Oreochromis macrochir (Boulenger, 1912)	I	HER	MOU	LC						†				S23
	Coptodon cameronensis (Holly, 1927)	E	HER	NES	LC	†				†			†		S24
	Coptodon rendalli (Boulenger, 1897)	I	HER	SUB	LC	†	†			†	†				S25
	Hemichromis camerounensis (Bitja Nyom et al., 2021)	N	PIS	NES	LC	†	†	†	†	†		†		†	S26
Total	26					13	10	7	3	8	6	4	4	2	

The fish species richness in the lakes decreased in the following order: Assom (13 species) > Bini (10 species) > Massote (8 species) > Dang (7 species) > Mbalang (6 species) > Ngaoundaba and Piou (4 species) > Gegouba (3 species) > Tizong (2 species). The last five lakes including all four crater lakes studied (Mbalang, Ngaoundaba, Gegouba and Tizong) and one undocumented lake (Lake Piou), were less rich.

Another interesting feature that emerged from these data in Table 3, was that no species colonized all nine lakes studied; the number of fish species that colonized one to eight lakes decreased drastically: 13 species (50%) only in one lake, 6 (23.1%) in two lakes, 2 (7.7%) in three lakes, and 3 (11.5%) in four lakes. Remarkably, *H. camerounensis* and *O. niloticus* were sampled in seven and eight lakes, respectively; they were the more ubiquitous species in the lakes.

In five lakes, Assom, Bini, Dang, Ngaoundaba and Tizong, the species richness of fish collected in the dry season was higher than in the wet season. Conversely, in Lake Mbalang, the species richness of fish collected in the wet season was higher than in the dry season. In lakes Gegouba, Massote and Piou, the species richness did not vary with season (Table 4).

Table 4. Seasonal variations of the ichthyofauna species richness in the different lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong). The seasons.

Lakes	Seasons	Species Richness
Bi	Dry	10
	Wet	7
Da	Dry	7
	Wet	6
As	Dry	13
	Wet	11
Ge	Dry	3
	Wet	3
Ma	Dry	8
	Wet	8
Mb	Dry	3
	Wet	6
Pi	Dry	4
	Wet	4
Ng	Dry	4
	Wet	3
Ti	Dry	2
	Wet	1

Among the 26 species collected from the Adamawa lakes, there were 20 (76.9%) native species, including at least three endemic to the Sanaga River (*C. cameronensis*, *P. similis* and *S. rebeli*) and none endemic to the Lake Chad Basin. Six species (23.1%) in the Sanaga River Basin (*C. rendalli*, *O. macrochir*, *L. niloticus*, *H. niloticus*, *O. niloticus* and *C. gariepinus*) and two (7.7%) in the Lake Chad Basin (*C. rendalli* and *O. macrochir*) were non-indigenous species. Two species (*Garra* cf *ornata* and *G.* cf *dembeensis*) had a doubtful status. *Garra* cf *ornata* is morphologically close to *G. ornata* (Nichols and Griscom, 1917), but with a wider body and a dorsal fin closer to the head; *Garra* cf *dembeensis* resembles *G. dembeensis* (Rüppell, 1835), but shows a narrower body and more scales. The status of four taxa (*Ctenopoma* sp., *Enteromius* sp. "mbalang", *Clarias* sp. "mbalang", and *Clarias* sp. "massote") could not be determined to species level.

3.4. Frequency of Trophic Groups

Four fish guilds were recognized in this work: herbivorous/detritivorous (HER: 23.1%), invertivorous (INV: 23.1%), omnivorous (OMV: 42.3%) and piscivorous (PIS: 11.5%) (Tables 3 and 5). The frequency distribution of these trophic groups also varied with site; the fish communities were essentially comprised of herbivorous and piscivorous (50% each in Lake Tizong; 66.7% and 33.3% in Lake Gegouba); herbivorous and omnivorous (50% for each in Lake Piou; 66.7% and 33.33% in Lake Mbalang); HER, OMV and PIS (respectively, 37.5%, 50% and 12.5% in Lake Massote; 25%, 25% and 50% in Lake Ngaoundaba); HER, OMV, INV and PIS (respectively, 20%, 20%, 40% and 20% in Lake Bini; 14.3%, 14.3%, 42.8% and 28.6% in Lake Dang; 23.1%, 30.8%, 38.5% and 7.7% in Lake Assom).

Table 5. Frequencies (%) of trophic groups (HER= herbivorous/detritivorous, INV = invertivorous, OMV = omnivores, PIS = piscivorous) and breeding groups (MOU = mouthbrooder, NES = egg nesters in sand plant or scum nests, SUB = open water/substratum egg scatters) in the different lakes.

Parameters		**Lakes**								
		As	**Bi**	**Da**	**Ge**	**Mas**	**Mb**	**Ng**	**Pi**	**Ti**
Trophic groups	HER	23.1	20	14.3	66.7	37.5	66.7	25	50	50
	INV	30.8	20	14.3						
	OMV	38.5	40	42.8		50	33.3	25	50	
	PIS	7.7	20	28.6	33.3	12.5		50		50
Breeding groups	MOU	7.7	10	14.2	33.33	12.5	16.7	25	25	50
	NES	30.8	30	42.9	33.33	25		50	25	50
	SUB	61.5	60	42.9	33.33	62.5	83.3	25	50	

3.5. Frequency of Breeding Groups

Among the 26 species sampled, 2 (7.7%), 6 (23.1%) and 18 (69.2%), respectively, incubate eggs in the mouth (BNI), keep their eggs in nests of scum, holes, sand or leaves (NES), or spawn in open areas or on substrates of sand gravel, rock or plants (SUB). The frequency distribution of these breeding groups varied with the study site. In seven sites (77.8%) the fish communities were comprised of the three breeding groups: mouth incubator (BNI), eggs keepers in sand plant or scum nest (NES), and spawn in water in open or various substrates (SUB), in different proportions (Tables 3 and 5). SUB fish were always most represented, except in Dang (their proportion equaled NES), Gegouba (their proportion equaled NES and BNI) and Ngaoundaba (NES predominated). They were absent in Tizong where the species richness of BNI and NES were similar. Lastly, no NES were collected from Mbalang.

3.6. Ecological Diversity of Fish Communities

The ecological indices varied between the ichthyofaunas of the different lakes (Table 6). The most diverse fauna was found in Lake Assom (H′ = 2.5; J = 0.97; d = 1.62) and the least diverse was in Lake Tizong (H′ = 0.57; J = 0.83; d = 0.18).

Table 6. Ecological indices of the ichthyofauna of the different lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong).

Sites	**Ecological Indices**								
	H′			**J**			**D**		
	General Values	**Seasonal Values**		**General Values**	**Seasonal Values**		**General Values**	**Seasonal Values**	
		Wet	**Dry**		**Wet**	**Dry**		**Wet**	**Dry**
As	2.50	2.48	2.41	0.97	0.96	0.97	1.62	1.74	1.71
Ma	2.04	2.04	2.03	0.98	0.98	0.97	1.09	1.17	1.29
Bi	1.94	1.99	1.84	0.84	0.86	0.94	1.21	1.99	0.89
Da	1.57	1.63	1.51	0.81	0.84	0.84	0.81	0.89	0.75
Pi	1.24	1.26	1.25	0.90	0.91	0.90	0.44	0.48	0.48
Mb	1.22	0.99	1.34	0.68	0.90	0.75	0.72	0.32	0.78
Ge	0.99	1.01	1.00	0.91	0.92	0.91	0.35	0.39	0.41
Ng	0.81	0.93	0.66	0.58	0.67	0.60	0.49	0.55	0.37
Ti	0.57	0.67	0.29	0.83	0.97	0.42	0.19	0.21	0.22

The diversity decreased in the following order: Assom (H′ = 2.53) > Massote (H′ = 2.04) > Bini (H′ = 1.94) > Dang (H′ = 1.57) > Dang (H′ = 1.57) > Piou (H′ = 1.24) > Mbalang (H′ = 1.22) > Gegouba (H′ = 0.99) > Ngaoundaba (H′ = 0.81) > Tizong (H′ = 0.57). This profile was quite similar (at least in 78.8% of cases) to Pielou (J) and Margalef (d) indices. Ichthyofauna of the crater lakes (Mbalang, Gegouba, Ngaoundaba and Tizong) revealed less diversity. Based on the Shannon–Weaver index, the diversity of the ichthyofauna appeared higher in the wet season than in the dry season, except in Lake Mbalang (Table 6).

3.7. Patterns of Fish Species Diversity and Its Distribution

Fish species composition showed different patterns in the nine lakes. NMDS (Figure 3) with a stress of 0.17 and one-way ANOSIM indicated that fish species composition significantly varied within lakes (R = 0.978, p = 0.0001). Significant pairwise differences in species composition were also observed among the nine lakes (Table 7).

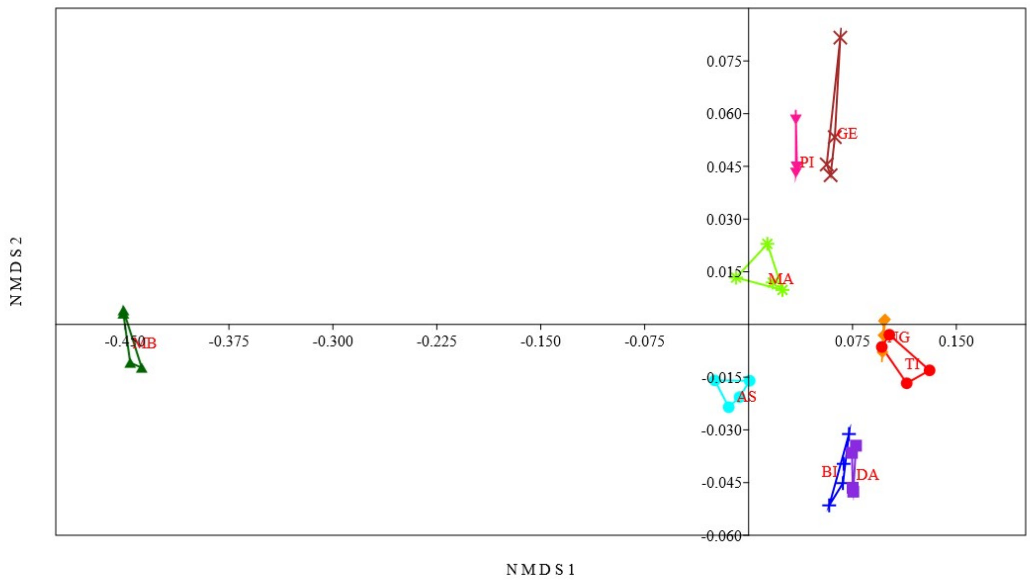

Figure 3. Ordinations of sampling sites by nonmetric multidimensional scaling (NMDS) based on the Bray-Curtis similarity matrix using seasonal fish species abundance data of nine lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong).

Table 7. p-values of the ANOSIM analysis (analysis of similarities) for the pairwise differences in species composition among the nine lakes (Bi = Bini, Da = Dang, As = Assom, Ge = Gegouba, Ma = Massote, Mb = Mbalang, Ng = Ngaoundaba, Pi = Piou, Ti = Tizong). Values in brackets represent global R.

Bi	0.0277 (0.70)							
Da	0.0284 (0.62)	0.0304 (0.73)						
Ge	0.0283 (0.53)	0.0261 (0.55)	0.0318 (0.50)					
Ma	0.0257 (0.64)	0.0289 (0.67)	0.0291 (0.61)	0.0285 (0.69)				
Mb	0.0312 (0.75	0.0296 (0.77)	0.0295 (0.75)	0.0271 (0.81)	0.0288 (0.80)			
Ng	0.0268 (0.71)	0.0289 (0.66)	0.0292 (0.69)	0.0272 (0.72)	0.0271 (0.61)	0.0318 (0.80)		
Pi	0.0277 (0.61)	0.0291 (0.69)	0.0275 (0.67)	0.0274 (0.42)	0.0302 (0.53)	0.028 (0.82)	0.0269 (0.73)	
Ti	0.0273 (0.70)	0.0272 (0.73)	0.0293 (0.72)	0.0274 (0.79)	0.0259 (0.74)	0.0289 (0.83)	0.0277 (0.30)	0.0221 (0.78)
	As	Bi	Da	Ge	Ma	Mb	Ng	Pi

SIMPER analysis revealed that *M. mento* contributed most to the dissimilarity between Lake Assom and the others (13.36%), *C. pachynema* contributed most to the dissimilarity between Lake Bini and the others (33.73%), *Ctenopoma* sp. between Lake Dang and the others (20.85%), *H. camerounensis* between Lake Gegouba and the others (43.18%), *C. cameronensis* between Lake Massote and the others (17.75%) and between Lake Piou and the others (22.47%), *O. macrochir* between Lake Mbalang and the others (22.91%), and *O. niloticus* between Lake Ngaoundaba and the others (43.82%).

3.8. Relationships between Environmental Variables and Fish Species

Canonical correspondence analysis (CCA) indicated the correlation between fish species and environmental variables (Figure 4); the first two axes explained 84.96% of the variation in fish species composition. The CCA results revealed, firstly, that some fish species, such as *H. niloticus*, *O. niloticus*, *H. camerounensis*, *Garra* cf *ornata*, *Garra* cf *dembeensis*, *O. macrochir*, were positively correlated to conductivity, TDS and Secchi disc depth, while *M. mento*, *E. martorelli*, *P. similis*, *C. jaensis*, *C. longior* were negatively related to these parameters. Secondly, these results revealed that *C. cameronensis*, *C. rendalli*, *S. rebeli* were positively correlated to the temperature and pH, while *L. niloticus*, *P. obscura*, *Ctenopoma* sp., *B. niger*, *C. cameronensis*, *C. gariepinus* were negatively correlated to these parameters.

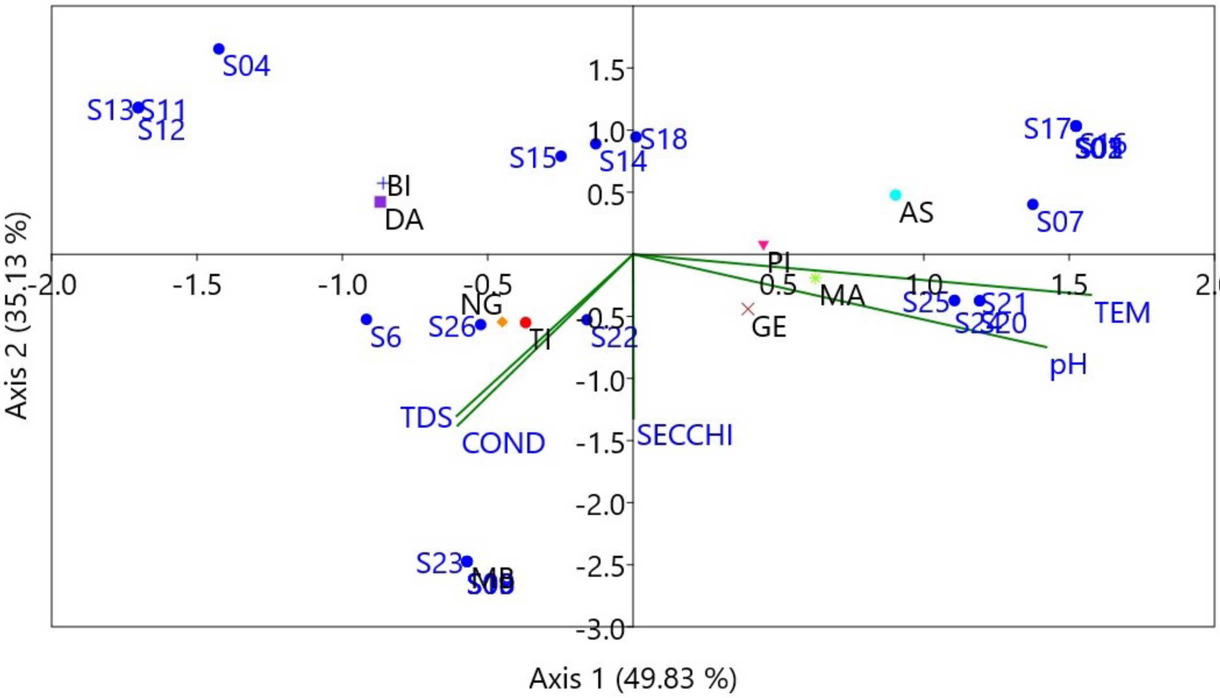

Figure 4. Biplots of canonical correspondence analysis displaying the relationship of fish species and environmental variables for all sampling sites (the abbreviations are summarized in Table 3).

4. Discussion

4.1. Comparative Limnology

The present study was carried out in nine lakes in the Adamawa region, Lake Assom being the ninth lake not listed previously by Kling [7]. Temperature is one of the most important parameters for fish growth [57], and the values obtained during the current work support the idea of Lemoalle [58], who observed that in intertropical Africa, the average temperatures are most often higher than 20 °C. The temperature was found to be higher in Lake Assom (Table 2) located at a low altitude (889 m), compared with other lakes located at high altitudes (over 1000 m). This result corroborates the results of Kling [7] who recorded (in Cameroon) temperatures above 25 °C in low altitude lakes. Lemoalle [58] also found a decrease in temperature with increasing altitude in some shallow African lakes. Temperature values in the crater lakes of Adamawa located at an average altitude of 1000 m were close to those of lakes in southwestern and northwestern Cameroon located at similar altitudes: this was the case of Lake Wum, whose temperature varies between 20.5 °C–25.5 °C [7].

Except for temperature, the other parameters (conductivity, TDS and transparency) were higher in all crater lakes (Gegouba, Mbalang, Ngaoundaba and Tizong) than in non-crater lakes (Assom, Bini, Dang, Massote and Piou), probably due to the location of these lakes in volcanic craters with bedrocks formed by magmatic rocks [7,30], their greater depth and smaller surface when compared with the others, and the absence (Tizong and Ngaoundaba) or seasonal presence (Gegouba and Mbalang) of a functional outlet [30]. Compared with non-crater lakes, the particular limnological characteristics of Adamawa crater lakes generally place them among relatively isolated aquatic environments [30]. The high transparency of the crater lakes is not surprising; their primary production, evaluated through concentration of chlorophyll a, is generally very low [7]. The low values of transparency recorded in lakes Bini and Dang were considered to be related to anthropization due to agricultural and pastoral activities practiced in the vicinity of these water bodies. In all the crater lakes of Adamawa, the depth at which the Secchi disk disappeared was above 3 m, while in the southwest and northwest lakes, it was only in Lake Barombi Kotto (0.75 m) and Lake Ejagham (3.95 m) that this depth was less than 4 m [7].

The low pH values of Lake Assom during the rainy season were remarkable. In the absence of agricultural and industrial activities around the lake, it can be postulated that this water acidification could be of natural origin, by leaching of the riparian lateritic soils rich in aluminum [31], or of anthropogenic origin by leaching of organic matter produced by the pastoral activities that take place around the lake; it could also have a dual origin (natural and anthropogenic).

4.2. Fish Species Composition and Distribution

In this study, we noticed that the variation of fish species composition and distribution between lakes was closely related to physicochemical parameters. The same results have already been found in six shallow lakes in the Yangtze River Basin in China [59]. In numerous African river basins, variations related to environmental variables are highlighted in fish species composition. In Ivory Coast, dissolved solids influence the distribution of *Hydrocynus forskahlii* (Cuvier, 1819), *Labeo coubie* (Rüppell, 1832) and *Distichodus rostratus* (Günther, 1864) in the main stream of the Sassandra River [60]; dissolved solids, pH and conductivity determine the distribution of *Enteromius ablabes* (Bleeker, 1863), *Chrysichthys maurus* (Valenciennes, 1839), *Petrocephalus bovei* (Valenciennes, 1847) and *Brycinus imberi* (Peters, 1852) in the Bandama River [61]; and pH regulates the structuration of *Marcusenius senegalensis* (Steindachner, 1870), *Brycinus macrolepidotus* (Valenciennes, 1850) and *Mormyrops anguilloides* (Linnaeus, 1758) in the Tai National Park rivers [62]. In Cameroon, *M. senegalensis* and *P. bovei* are very dependent on dissolved oxygen in the Lower Ntem River [63]; conductivity and total dissolved solids determine the distribution of *P. kingsleyae* and *B. brachyistius* in the Djerem River alongside the man-made Mbakaou Lake [54]. Interestingly, Lake Mbakaou is close to lakes Assom, Massote and Piou, which were considered in this study. Therefore, it is not surprising that *C. cameronensis* and *S. rebeli*, present in the Djerem River, were also inventoried in these three lakes which registered the same values of physicochemical parameters. Except in Lake Mbalang, fish species richness decreased from dry to wet season and affected the specific diversity. This could be due to the fact that during the rainy season, the abundance of rain increases dispersion of fishes, which results in decreasing fishing efficiency [64]. Lower specific diversity can also be affected by selectivity of fishing gear used [65]. The seasonal variations observed in this study could also be determined by variations of water physicochemical parameters, as is the case at Lake Assom, where we noticed that decreasing fish diversity in the wet season correlated to the decrease of pH and transparency [66].

In addition to physicochemical parameters, other main factors that potentially influenced fish species composition and distribution in the Adamawa lakes were the origin of the lake (crater lake or non-crater lake), depth, surface, and absence or presence of an outlet [30]. In addition to these factors, altitude appears to have played an important role in limiting species richness in Adamawa crater lakes, compared with the southwest lakes of Cameroon which host fish species flocks. In the northwest region, both the altitude and repetitive lethal explosion or accumulation of gases in some craters seem to have played this role [8,9,13,14]. The available evidence is that breeding populations of fish must surely have been introduced into Lake Nyos on a number of occasions, but whenever this has happened, a subsequent lake overturn, similar to what caused the August 1986 disaster, completely deoxygenated the surface water and killed all the fish. As there were no fish in the lake before the recent disaster, it is likely that major gas releases are rather more frequent than the natural introduction of viable fish populations. In fact, it was speculated that major gas releases might occur approximately every 50 years [26].

4.3. Specific Wealth

The present study identified 26 fish species distributed across seven families. This represents the first data on the ichthyological fauna of the Adamawa lakes. In the northwest lakes including Monoun, Nyos and others (e.g., Baleng and Wum), the ichthyofauna is poorly diversified and estimated to more than five species classified into two families (Cichlidae and Cyrpinidae) [8]. In the southwest lakes (Barombi Mbo, Barombi Kotto, Bermin, Ejagham, Dissoni/Soden, Manengoumba and Mboandong), Trewavas [13] and Bitja Nyom [8], recorded more than 39 species divided into four families (Clariidae, Cyprinidae, Mochokidae, and Cichlidae), with a large number (35) of these species belonging to the Cichlidae. These results are different from some African lakes: Lake Malawi holds the record with 545 species currently described, followed by Lake Tanganyika with 301 species, and the Victoria and Kyoga lakes system with 288 species [67]. The fish diversity of the Adamawa lakes appeared higher than those of the Ethiopian Rift which contain only a few species of catfish, tilapia and barbus [68,69]. Our results are also different from those of Anabi and Issiaka [70] who found 40 fish species belonging to 17 families in Lake Madarounfa (Niger).

4.4. Origin of Ichthyofauna and Speciation in the Adamawa Lakes

Initially, we were interested in the diet and modes of reproduction of the species present in the lakes studied. The purpose of the current analysis was to verify whether environmental parameters would have resulted in possible fish speciation in the Adamawa lakes. Although herbivores, carnivores and omnivores were found, our results showed that these faunas were composed of 76.9% native and 23.1% non-indigenous species. Although at least three endemic species of the Sanaga River Basin were also identified in its lakes, no apparent speciation was formerly demonstrated for these lakes, to our present knowledge. Interestingly, six native species inventoried in surrounding rivers were also found in crater lakes. Our observations differed from those made on the ichthyofauna "species flock" of the lakes of southwest Cameroon, which have undergone sympatric speciation on various food and reproductive nests [8,12,16,71,71], as well as with respect to their water depth preference [16] and repeated gene flow between radiations and neighboring riverine populations, including allopatric and sympatric phases after initial colonization [21]. It is unlikely that such a phenomenon does not seem to occur in high altitude lakes such as Adamawa [8]. Other assumptions have already been made about speciation in lakes. During the last ice ages, the high-altitude lakes did not function as refuges, such as those in low and medium altitudes, which are currently rich in endemic species. Actually, during the dry phase (around 3000 years BP), lakes Barombi Mbo, Barombi Kotto, Mboandong and Bermin would have functioned as refuge areas [72–74]. However, if the high-altitude lakes had experienced radiation before these arid periods, they would obviously have been refuges for these species flocks since the mountainous areas, where they are located, have functioned as such for terrestrial organisms [75,76]. Loheac et al. [77] emphasized that fish present in European high-altitudes were mostly introduced species and did not experience speciation. As colonization of the lakes was essentially of fluvial origin, the riparian lineages did not succeed to cross the various tectonic accidents that very often exist along the rivers and mountain torrents connected to some of these lakes. Indeed, the falls allow the passage of species from upstream to downstream but not in the opposite direction, or very little [78,79].

Although they are of high altitude, the better way to understand the origin of native fish species present in the Adamawa crater lakes is to postulate that these lakes were probably permanently connected to surrounding rivers in the past before losing their outlets, or the outlets were only seasonally used as currently observed, while natural depressions or man-made lakes retained their connections to surrounding rivers, making possible the free flow and exchange of organisms. Recent observations have shown that the insulation of Lake Tizong may have exerted an evolutionary pressure on its *H. camerounensis* population, which responded by a tendency to size reduction of fish, illustrated by the dominance of small-sized individuals in the catches, compared with both populations of the same species in lakes Dang and Bini [30]. According to Temdjim [80], the Adamawa lakes seem younger than those of southwest and northwest Cameroon; this could imply that their fish faunas are too young to show speciation processes.

The non-indigenous species inventoried in all the lakes were probably introduced by human activities such as fisheries. Some of these introductions of non-indigenous species were accidental [81] or intended to develop aquaculture and fishing, and to improve the productivity of natural environments [82]. Unfortunately, since the spread of non-indigenous species is recognized as a major threat to freshwater biodiversity [83,84] introduced predator fish such as *L. nitloticus* or non-predator fish such as *O. niloticus* and *O. macrochir* can compete with indigenous species and eventually eliminate them [85–87]. According to [81], stocks of *O. niloticus* from the Chad Basin (Chad and Central African Republic) and those probably consisting of a mixture of *C. rendalli* and *C. zillii* from the Congo Basin (Democratic Republic of Congo), would have been introduced into the Sanaga Basin, in particular in the Noun, Djerem and Lom marshes, between 1949 and 1975. It is not surprising that these species are found in lakes Assom, Massote, Piou and Gegouba, which are connected to the Djerem River.

Conversely, our observations differed from those made on the ichthyofauna "species flock" of the East Africa Great Lakes which are known as biodiversity hot-spots. These long persisting freshwater bodies are typically very deep, rather isolated, and usually house extremely species-rich biological communities featuring exceptional levels of endemism [88]. The extraordinary fish species richness of these lakes is often the product of intralacustrine adaptive radiations, in the course of which a common ancestor diversifies rapidly into new, phenotypically-distinct species that occupy the available ecological niche space [89–91]. The extraordinary species richness could also be due to the fact that the East Africa Great Lakes are the oldest in the world: about 20 million years old for Lake Tanganyika, and 2 to 10 million years for Lake Malawi [92].

Some native species of Cameroon, mainly from the Sanaga Basin, were inventoried in this work; observed species were *P. similis* and *M. mento* (Lake Assom), *S. rebeli* (Lake Massote), and *H. camerounensis* (in all lakes, except in Gegouba, Mbalang and Piou). *P. similis* and *M. mento*, two of the most sensitive species to pollution, overfishing and invasive species [54], were already known in the upper Sanaga [55,58,93]. Their presence in Lake Assom could be explained by the fact that this lake is poorly impacted by pollution and fishing activities, and remains connected to the Djerem River through an outlet making possible the free flow and exchange of organisms. These fish species lost their habitat in the area impacted by the Mbakaou dam through pollution, overfishing and introduction of alien species [54]. *S. rebeli* is endemic to the Sanaga River Basin [28]; its presence in Lake Massote of the Sanaga hydrographic basin is understandable. *H. camerounensis*, collected in most lakes, is endemic to Cameroon [94] and would have colonized the Sanaga River Basin, i.e., lakes Assom, Ngaoundaba, Massote, Tizong, and Lake Chad Basin (Bini, Dang) [94]. However, the presence of *S. rebeli* and *C. cameronensis* in the Adamawa lakes could be due to their strong resilience [54]. We also noted the presence of *C. pachynema* and *C. camerunensis* in the Lake Chad Basin (Bini and Dang). The presence of *C. jaensis*, *C. longior*, *E. martorelli*, *P. kingsleyae* in our samples was not surprising, because the waterbodies in which there were collected correspond to the area where they were already known [41,42].

5. Conclusions

For the first time, an ichthyological study has been carried out on fish stocks of nine lakes in the Adamawa region of Cameroon. The ichthyofaunas of these lakes are not very diversified. Native species of the local hydrographic system, as well as introduced species, are found there—indeed, they are fish species previously reported in Lower Guinea and West Africa. Six are non-indigenous species and also good candidates for aquaculture purposes (*C. rendalli*, *O. macrochir*, *L. niloticus*, *H. niloticus*, *O. niloticus* and *C. gariepinus*), while at least three (*C. cameronensis*, *P. similis* and *S. rebeli*) are endemic species in the Sanaga Basin and should be managed for conservation in lakes Assom, Gegouba, Massote and Piou. Moreover, six other taxa (*Garra* cf *ornata*, *G.* cf *dembeensis*, *Ctenopoma* sp., *Enteromius* sp. "mbalang", *Clarias* sp. "mbalang", and *Clarias* sp. "massote") inventoried in three lakes (Bini, Massote and Mbalang) have an undetermined taxonomic status and are included in the supplementary ongoing studies; they are considered as probably native. This preliminary study is essential for increasing knowledge of the fish fauna of Cameroon. Several factors determine the fish species composition in the Adamawa lakes, such as the origin of lake (crater or non-crater), altitude, depth, surface, and absence or presence of an outlet. *H. camerounensis*, newly described as commonly distributed in Cameroon, was present in all the lakes, except in lakes Mbalang and Piou. The most important threats to ichthyofauna in the Adamawa lakes are the presence of non-indigenous species that can replace native species, uncontrolled fishing, and pollution caused by agricultural and pastoral activities. Based on the fact that there is a growing recognition of the need to conserve biodiversity, that has been conceptualized in the Convention of Biological Diversity, maintenance of fish species richness is particularly important because habitat degradation in inland waters continues to accelerate on a global scale.

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