Tanzania Journal of Science 47(5): 1890-1900, 2021
ISSN 0856-1761, e-ISSN 2507-7961

Anticipating the Effects of Increasing Rivers' Water Salinity for Sustainable Conservation of Tilapia Resources in Rural Coastal Zone of Benin, West Africa

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Received 5 Sep 2021, Revised 30 Dec 2021, Accepted 31 Dec 2021, Published Dec 2021

DOI: https://dx.doi.org/10.4314/tjs.v47i5.33

Abstract

The current research aimed at using the application of multi-factor models to support fisheries management decisions for successful resources' conservation. The study was based on the tilapia species *Coptodon guineensis*, which is among the most widely exploited in Benin coastal zone. In an attempt to suggest conservation strategies, the phenotypic variability of 356 accessions of this species was assessed in relation with water salinity, and several interactions. The fish were collected through small-scale experimental fishing using cast nets and gillnets. The findings indicated that the salinity observed in the sampled rivers is due, at proportions ranging from 0.13% to 47%, to the sea surface salinity (SSS) of the Atlantic Ocean, suggesting a leading inland origin of the salinity of these rivers. The evidence also showed that the tilapia populations have been relatively adapted to the increasing water salinity of the sampled rivers. The fish species*river type and fish species*fish sex interactions had significant effects on phenotypic characteristics rather than river type*fish sex interaction. For an efficient conservation of these populations, two conservation areas (Lake Nokoué and Porto-Novo lagoon *vs* Lake Toho and Grand-Popo lagoon), could be considered for this tilapia species.

Keywords: Aquatic salinization, population adaptation, growth parameters, interaction patterns.

Introduction

Nowadays, it is important to fully understand the aquatic ecosystems for better and appropriate uses of resources in order to preserve African coastal aquatic biodiversity. This challenge is the top priority of the Millennium Development Goals as well as the Sustainable Development Goals established by the United Nations, which included linking socio-economic and environmental sustainability to protect and restore biodiversity (UN 2017).

In Benin coastal areas, aquatic ecosystems are still under six types of ongoing threats: over-exploitation, water pollution, sand-mining, fish diseases, invasive species, and climate change facilitated by migration and population growth (Teka et al. 2012, Adite et al. 2013, Amoussou et al. 2017). Aquatic genetic resources are thus affected by these undesirable drivers that create species population fragmentations by increasing inbreeding rates resulting in a reduction of genetic variability as well as species extinction. Many fish species from the salty water ecosystems are considered endangered because of the reduction of their distribution area and their stocks abundance.

The tilapia species *Coptodon guineensis* (Günther, 1862) is among the most representative species of the estuaries and lagoons ecosystems in Benin (Adite et al. 2013). It is a substrate-breeding species that is widespread in three African regions: West Africa, Central Africa and Southern Africa, i.e. from Senegal to Angola (Paugy et al. 2004). The species has a relative frequency of citation of 77.34% in the coastal mangrove zone (Gnansounou et al. 2021). Individuals caught in Lake Nokoué and Porto-Novo lagoon have a total length between 4.6 and 21.8 cm (Lederoun et al. 2018). The species is an ecologically interesting model as it shows exceptional adaptive capacities to high salinity flow (Chukwu and Okpe 2006, Labonne et al. 2009). This species is naturally adapted to the coastal lagoon environment and has not been the subject of any conservation and management programme. Therefore, there is a need to contribute to the conservation and sustainable use of this aquatic natural resource and ecosystems through integrated climate actions (EU 2019) for fisheries and aquaculture.

In the context of salinization in the aquatic environment, the question is 'to what extent does the rise in salinity affect the phenotypic characteristics of *C. guineensis*'? Thus, the scope of this research spans the phenotypic variability of populations of this tilapia species with a focus on its link to the salinity of inland rivers. This research is two-fold; on one hand, it analyzes the relationship between "the salinization in Benin coastal areas" and "the tilapia population adaptation", and on the other hand, the relationship between "the salinity flow of the rivers" and "the phenotypic characteristics of the tilapia species". The last part of this research focused on the identification of conservation areas for the various populations' sustainability.

Materials and Methods

Study area

The country has a coastline of about 121 km bordered by a series of lagoons of about 333 km^2 and many rivers and reservoirs. The coastal complex flows into a lagoon system (Figure 1). The lagoon system is organized as follows: Lake Toho and Grand-Popo lagoon are in the Mono-Couffo River basin, while Porto-Novo lagoon and Lake Nokoué are in the Ouémé-Yéwa River basin. Lake Nokoué, a shallow lake covering about 160 km^2, comes into direct contact with the Atlantic Ocean via a lagoon channel. Lake Toho, located in the southwest of the country, covers an area varying from 9.6 to 15 km^2. The Grand-Popo lagoon, covering an area of about 15 km^2, constitutes a part of the country's coastal lagoon. Porto-Novo lagoon, covering about 20 km^2, belongs to the equatorial climatic zone, while the other three rivers are in the subequatorial zone. The fishers operating on these different rivers belong to the village-based riparian communities. The fishing equipment usually deploy to catch fish are: gill nets, cast nets, keep nets, acadjas, fish hooks, net-enclosures, scoop nets and long lines.

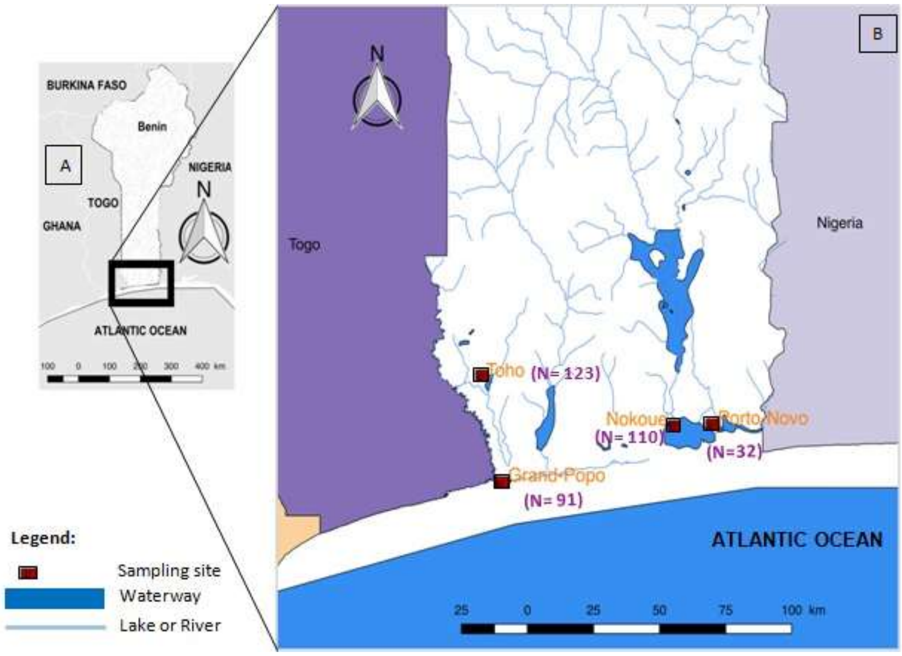

Figure 1: Map of Benin coastal zone showing the selected rivers and the tropical Atlantic Ocean. N: sample size.

Sampling methods

The accessions of the tilapia species *Coptodon guineensis* (Günther, 1862) were experimentally sampled for 12 months in the coastal area of Benin from January to December 2018. The sampling periods were the same for all the species accessions. Ten phenotypic characteristics were measured *in situ* on each accession, using digital calipers (with a precision of 0.1 cm). Tilapia species identification and phenotypic measurements were carried out as stated in Paugy et al. (2004), and were defined as follows: Total length (TL: horizontal distance from front tip of snout to hind tip of caudal fin); Standard length (SL: horizontal distance from front tip of snout to base (or articulation) of caudal fin); Body depth (BD: maximum vertical depth of fish, excluding fins); Predorsal length (PDL: horizontal distance from front tip of snout to the articulation of first dorsal-fin ray); Preanal length (PAL: horizontal distance from front tip of snout to the articulation of first anal-fin ray); Prepectoral length (PPL: horizontal distance from front tip of snout to the articulation of first pectoral-fin ray); Prepelvic length (PPeL: horizontal distance from front tip of snout to the articulation of first pelvic-fin ray); Depth of caudal peduncle (DCP: minimum vertical depth of caudal peduncle); Dorso-anal length (DAL: vertical distance from front tip of dorsal fin to lower tip of anal fin), and body weight (W). The sex of each tilapia accession was identified through manual sexing by observing the genital papilla under a magnifying glass. Additionally, when no sperms or eggs were obtained during sexing, the fish gonads were extracted in order to confirm the sex. In all, 356 accessions of *C. guineensis* were sampled randomly and systematically in the four-targeted rivers without distinction of the fishing gear. For each small-scale experimental fishing, the fishing gear used was the same as that of the fishermen. All these fishing were mainly carried out with cast nets and gillnets. The four rivers were targeted given the ecological importance of the tilapia species within them. The rivers' water salinity was recorded *in situ* using a portable Multimeter (Hanna®). However, the tropical Atlantic Ocean salinity data were retrieved from the French SSS (Sea Surface Salinity) observation service and are available at http://www.legos.obs-mip.fr/observations/sss.

Data processing and analysis

Data were processed and depicted using GraphPad Prism 6.0 and statistically analyzed using R software (R Development Core Team 2019). Parametric tests were used since data accuracy and exploratory analysis showed normal distribution. The interaction patterns were analyzed and allowed to model the relationship between the phenotypic characteristics and the three factors: ‘the fish species combined with the river of origin’, ‘the fish species with the fish sex’, and ‘the sampling river together with the fish sex’. The interaction between the sampled river and the fish sex was not significant ($p > 0.05$). Accordingly, the model used was fitted as $y_{ijkl} = \mu + \alpha_i + \beta_j + \lambda_k + \delta_{ijk} + \sigma_{ik} + \xi_{ijkl}$, where: y_{ijkl} is the phenotypic observed value for the i^{th} specimen coming from the j^{th} sampling river and having the k^{th} sex; μ is the grand mean of the phenotypic observed value; α_i is the species effect; β_j is the river effect for the j^{th} sampling river, the river effects may be either Grand-Popo lagoon or Lake Nokoué or Porto-Novo lagoon or Lake Toho; λ_k is the fish sex effect for the k^{th} sex, the sex effects may be either male or female; δ_{ijk} and σ_{ik} are the two-way interaction terms; ξ_{ijkl} is the random error associated with the y_{ijkl} exploratory model investigated. All the interactions were visualized first through boxplots and interaction plots. Assuming that all variances are unequal (var.equal = FALSE), Student’s t-test was undertaken for pairwise comparison between groups by considering a bilateral variation of data (alternative = ‘two.sided’).

The degree of fish well-being and the fish adaptability was estimated computing Fulton’s condition factor ($K' = (W/SL^3)*100$) (Nash et al. 2006). This parameter is known to be influenced by changes in seasons, breeding periods, sexual differences, age, gonad maturity levels, nutritional levels and maturity of fishes (Nyakuni 2009, Zuh et al. 2019). This parameter is also used as a measure of the physiological stage of fish (Oni et al. 1983) since it may decrease during periods of intense reproductive activity. In this study, the condition factor was useful in understanding the impacts of variations in salinity conditions in the aquatic environment on the tilapia species. To assess population growth, the relations between length and age of the tilapia fish samples were analyzed from the four rivers. Indeed, the monthly population length-frequencies grouped by constant class size was used as input in FiSAT II (Gayanilo et al. 2005). The matrix was also characterized by the lower and the upper class limits, and a "mid-length". The von Bertalanffy growth model was then used to determine the asymptotic length of fish L_∞ and the growth coefficient K. The model was of the form $TL = L_\infty (1 - e^{-K(t - t_o)})$, where: TL is the total length of the fish specimen at time t; L_∞ is the asymptotic length of fish in cm; K is the growth coefficient in year^{-1}; t_o is the age at length zero in year. The estimates of L_∞ and K were used to compute the growth performance index Ø’ known as the equation $Ø' = \log_{10}K + 2 \times \log_{10}L_\infty$ (Pauly and Munro 1984). The growth performance index Ø’ helped to compare the growth performance of the tilapia species between the four sampled rivers. The age at length zero t_o was estimated using Pauly’s empirical equation $\log_{10}(-t_o) = -0.392 - 0.275\log_{10}L_\infty - 1.038\log_{10}K$ (Pauly 1979).

To measure the strength of the linear relationship between phenotypic characteristics, Pearson’s correlation was used. The phenotypic correlations were visualized first by using the code ‘pairs (data[,1:10])’. This allowed choosing the phenotypic parameters to be considered for Pearson’s correlation computing. The significance of the relationship was tested with a unilateral Pearson’s correlation test through the cor.test function. Likewise, a linear regression approach was used to model the relationship between seawater salinity and rivers’ salinity. The lm (linear model) function allowed linear models to be adjusted. Since the phenotypic parameters were co-linear (highly correlated), a Principal Component Analysis (PCA) was not performed directly. Instead, the relationships between the different tilapia populations, through cluster analysis using the Cluster package, were initially assessed. The resulting entities (clusters) were then subjected to a PCA through the FactoMineR package and helped characterize all the identified conservation areas.

Results

Aquatic salinization and Tilapia population adaptation

The ocean SSS explained a tiny part of the salinity of the water sampled from the different rivers (Figures 2D, 2E, 2F and 2G). Grand-Popo lagoon was the most influenced by the ocean salinity ($R^2 = 0.47$). The water salinity at Grand-Popo lagoon was significantly correlated with the Ocean salinity (*p*-value = 0.01417) with a 95% confidence interval of [-0.903.-0.181]. The Ocean salinity explained at least 15.28%, 0.13% and 14.58% of the water salinity variations in Lake Nokoué, Porto-Novo lagoon and Lake Toho, respectively. These variations were significantly similar ($p > 0.05$), but positively correlated and weakly linked to the salinity of the seawater. The SSS averaged 35008 ± 111.1 mg/L, while the rivers salinities averaged 4.72 ± 0.73 mg/L, 2.44 ± 0.31 mg/L, 2.58 ± 0.33 mg/L and 0.17 ± 0.07 mg/L, respectively in Grand-Popo lagoon, Lake Nokoué, Porto-Novo lagoon and Lake Toho.

Tilapia populations have been relatively adapted to the increasing water salinity of the sampled rivers, since K' > 3 overall its estimates (Figures 2A, 2B, and 2C). *C. guineensis* accessions from Lake Nokoué, Porto-Novo lagoon, Grand-Popo lagoon had the highest condition factors compared to accessions from Lake Toho (*p*-value < 0.01). Indeed, only accessions from Lake Toho had the lowest condition factor (4.1 ± 0.05). Analyzing the fish species and the fish sex together, resulted in a significantly similar condition factor in both male and female accessions. We detected no significant differences in the condition factors for the interactions between the river of origin and the sex of the fishes.

The growth parameters, namely the asymptotic length of fish L_∞, the growth coefficient K, the age at length zero t_o, the growth performance index Ø' of the populations of the tilapia species are reported in Table 1. Extreme values of the asymptotic length of fish L_∞ estimates were 11.07 ± 0.211 cm and 11.73 ± 0.422 cm overall accessions. The growth coefficient K ranged from 1.2 ± 0.032 year^{-1} to 1.3 ± 0.063 year^{-1} overall subsamples. The age at length zero t_o varied from -0.17 ± 0.007 to -0.16 ± 0.008 overall subsamples. The populations of *C. guineensis* had growth performance index values ranging from 2.17 ± 0.03 to 2.23 ± 0.046.

Table 1: Estimates of the parameters (estimate ± standard error) of the von Bertalanffy Growth Function (VBGF) of *C. guineensis* accessions from Benin

River	L_∞	K	t_o	Ø'
Grand-Popo Lagoon	11.07 ± 0.211 cm	1.23 ± 0.042 year^{-1}	-0.17 ± 0.006 year	2.17 ± 0.03
Lake Nokoué	11.73 ± 0.422 cm	1.27 ± 0.053 year^{-1}	-0.17 ± 0.007 year	2.23 ± 0.046
Porto-Novo Lagoon	11.73 ± 0.422 cm	1.2 ± 0.032 year^{-1}	-0.17 ± 0.005 year	2.21 ± 0.04
Lake Toho	11.4 ± 0.316 cm	1.3 ± 0.063 year^{-1}	-0.16 ± 0.008 year	2.21 ± 0.042

L_∞ is the asymptotic length of fish in cm; K is the growth coefficient in year^{-1}; t_o is the age at length zero in year; Ø' refers to the growth performance index.

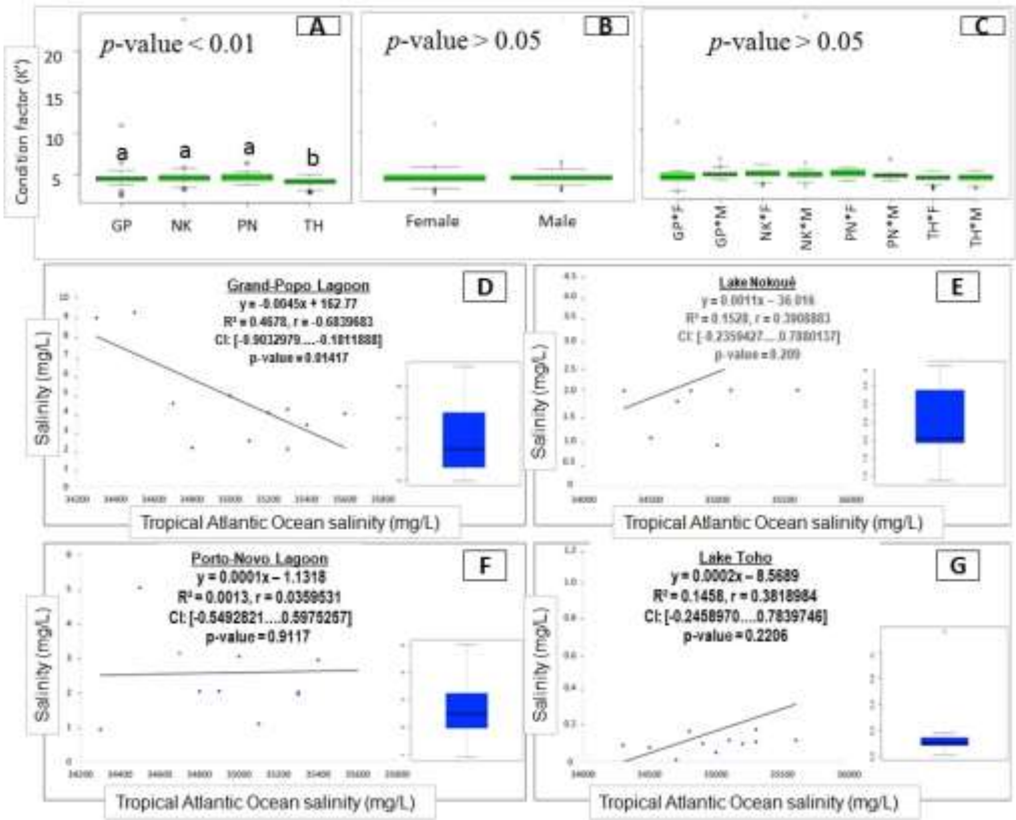

Figure 2: Boxplots A, B and C represent condition factors (K') within tilapia populations for each of the interactions investigated. Each condition factor's mean values that do not share the same superscript(s) differ significantly in the effects of the interactions at 5%. Regression plots D, E, F, and G represent the relationships between *in situ* water salinities of rivers and SSS, along with the blue color boxplots of the different water salinities. Regression plots were built on the basis of average salinity values. R^2 and r refer respectively to the coefficient of determination and the Pearson linear correlation coefficient of salinity values between the sampled rivers and the Tropical Atlantic Ocean. Each boxplot shows the boxplots, median, 25th and 75th percentiles, while points are outliers.

Interaction patterns of phenotypic characteristics

Here, interactions were investigated as presented in Figure 3, and Table 2 to identify drivers that could influence the success of a potential conservation programme. The evidence shows that, apart from the depth of caudal peduncle, all other phenotypic characteristics were significantly higher (*p*-value < 0.05) in Lake Nokoué and Porto-Novo lagoon than in Grand-Popo lagoon and Lake Toho (Table 2) despite the fact that all accessions were sampled together in same periods. The different comparisons made it possible to know which phenotypic characteristics are influenced by the cumulative effects of the three factors: species, fish sex and river. Overall, the river type*fish sex interaction was not significant, while the fish species*river type and fish species*fish sex interactions had significant effects on phenotypic characteristics. In addition, interactions between factors of the model revealed that the phenotypic characteristics were mostly influenced by the dual effect (here interaction) of the fish species and rivers. In fact, the fish species*river type interaction had significant effects on the body weight of the fish accessions (p-value < 0.05) (Figure 3C). However, the individual fish weight of the accessions was not significantly influenced by the cumulative effects of fish species and fish sex interaction (Figure 3D). With this interaction, the highest individual weights were recorded among *C. guineensis* accessions coming from Lake Nokoué and Porto-Novo lagoon (Figure 3C). The depth of caudal peduncle was not influenced by the fish species*river type interaction (Table 2) suggesting that the difference in this character value between the groups is the same in all the environments. For all the eight other metric parameters, one factor of the model alters the effect of the other factor; accordingly, there is a significant interaction (Table 2). Indeed, these phenotypic characteristics were significantly (p-value < 0.05) affected by the fish species*river type interaction. In addition, Grand-Popo lagoon, Porto-Novo lagoon, and Lake Nokoué hold waters that have higher salinity in comparison to Lake Toho and the lowest values of phenotypes were recorded among accessions that were recorded from Lake Toho (Table 2). This confirmed the adaptation of the species to the lagoons and estuarine ecosystems. The fish species*fish sex interaction indicates that there is no sexual dimorphism in *C. guineensis* with respect to the phenotypic characteristics that did not vary significantly (Figure 3B). In addition, the effect of rivers*fish sex interaction has no significant effects on phenotypic characteristics.

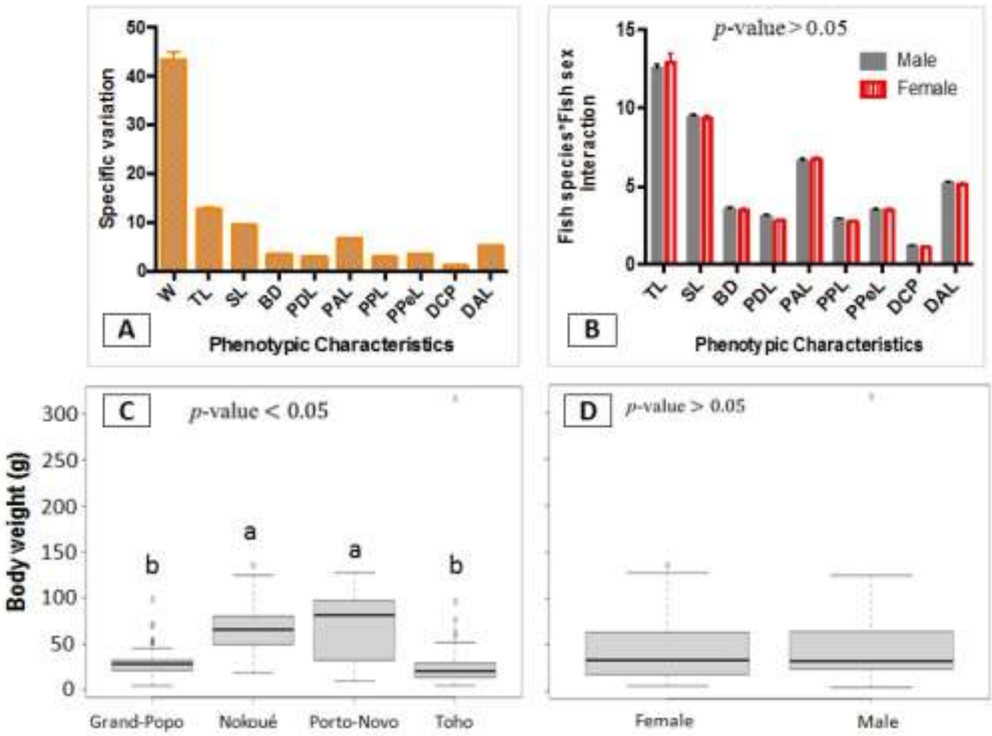

Figure 3: Boxplots of the fish weight (C and D), and graphs (A and B in means ± standard errors) of the phenotypic characteristics according to the crossing of the modalities of the three factors. Each graph shows the boxplots (C and D), the median, 25th and 75th percentiles, while points are outliers. Each phenotypic parameter's mean values that do not share the same superscript(s) differ significantly in the effects of the interactions at 5%.

Table 2: Mean values of phenotypic parameters (± standard errors of fish species*river type's interaction means) under the fish species*river type interaction during the sampling period

	Grand-Popo Lagoon	Lake Nokoue	Porto-Novo Lagoon	Lake Toho	Significance
	M ± SE	M ± SE	M ± SE	M ± SE	
Total length	11.08 ± 0.19^{b}	14.94 ± 0.16^{a}	14.71 ± 0.5^{a}	11.54 ± 0.77^{b}	*
Standard length	8.35 ± 0.14^{b}	11.25 ± 0.12^{a}	11.06 ± 0.38^{a}	8.2 ± 0.17^{b}	***
Body depth	3.17 ± 0.08^{b}	4.5 ± 0.06^{a}	4.42 ± 0.18^{a}	2.83 ± 0.08^{c}	***
Predorsal length	3.05 ± 0.15^{b}	3.28 ± 0.05^{a}	3.22 ± 0.11^{a}	2.62 ± 0.06^{c}	*
Preanal length	5.69 ± 0.14^{c}	7.84 ± 0.14^{a}	8.04 ± 0.27^{a}	6.07 ± 0.13^{b}	***
Prepectoral length	2.61 ± 0.07^{b}	3.39 ± 0.05^{a}	3.34 ± 0.13^{a}	2.4 ± 0.05^{c}	**
Prepelvic length	2.88 ± 0.05^{d}	4.39 ± 0.13^{a}	3.8 ± 0.12^{b}	3.1 ± 0.1^{c}	***
Depth of caudal peduncle	1.04 ± 0.1^{a}	1.45 ± 0.03^{a}	1.37 ± 0.06^{a}	0.92 ± 0.03^{a}	NS
Dorso-anal length	4.52 ± 0.1^{b}	6.39 ± 0.07^{a}	6.21 ± 0.23^{a}	4.42 ± 0.11^{b}	***

Mean values that do not share the same superscript(s) differ significantly in the interactions effects at 5%; ***: p-value < 0.001; **: p-value < 0.01; *: p-value < 0.05; NS: p-value > 0.05.

Population typology

Overall subsamples, the phenotypic characteristics were significantly and positively correlated with each other. These important degrees of linkage found are represented in Figure 4A. In *C. guineensis*, the depth of caudal peduncle was weakly (r = 0.02483) and moderately (p-value = 0.01052) correlated with the total length and the predorsal length, respectively. The nine-other phenotypic characteristics were highly (p-value < 0.001) correlated with each other. The species pointed to at least two clusters. For *C. guineensis*, Cluster 1 is made up of specimens from Lake Nokoué and Porto-Novo lagoon, while Cluster 2 is made up of specimens from Lake Toho together with those of Grand-Popo lagoon (Figures 4B and 4C). The cumulative percentage of variance of the PCA showed that dimension 1 explains nearly 100% of the variations. Dimension 1 mainly opposed Cluster 1 to Cluster 2 in *C. guineensis* accessions. Indeed, specimens in Cluster 1 are characterized by high values of the ten phenotypic parameters, while an opposite pattern has been observed for specimens in Cluster 2 (Figures 4B and 4C). The observed clusters are indicators of the conservation areas for each group.

Discussion

The variations of the water salinity of the samples from the rivers are relatively explained by the SSS. Grand-Popo lagoon is the most subject to the SSS (46.78%, p-value = 0.01417). The water salinity in the three other rivers being very slightly (0.13% to 15.28%, p-value > 0.05) explained by the SSS. A leading inland origin of the salinity of these waters could be confirmed given the low impact of the ocean. This is a significant finding because the flows of pollutants production occurring in the inland zones result in releases of polluting substances into the environment, particularly into the surface waters. Indeed, the presence of garbage dumps on the shores of the lagoons, sewage runoff into the lagoons is irrefutable proof of this. Under such a condition, integrated and participatory approaches (perception of the local affected dwellers) are worth adopting to ensure the sustainability of the aquatic ecosystem and resources (Teka and Vogt 2010), although a response to selective pressures has previously been suggested in *C. guineensis* (Bower et al. 2018). Beyond the adaptive response, this species has demonstrated fast growth (Francis and Ebere Samu 2010) or slow growth (Adedolapo 2015) depending on the habitat.

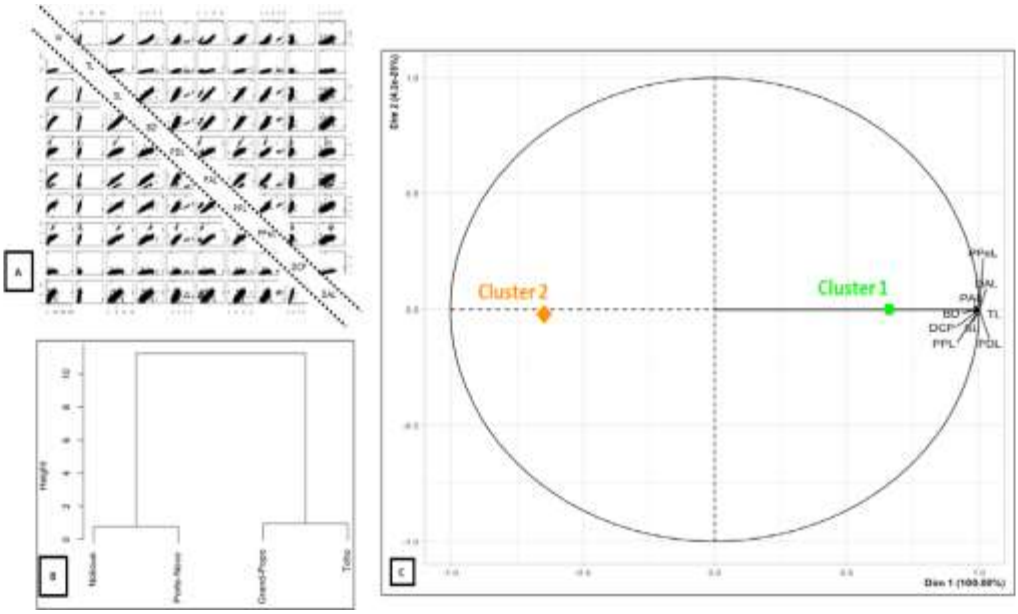

Figure 4: Pearson correlation statistics (A), Cluster Dendrogram (B), and Principal Component Analysis (C) overall phenotypic characteristics of *C. guineensis* accessions from Benin.

Here, it was discovered that there is a specific relationship between species and water salinity. Interactions between factors of the model revealed that the phenotypic characteristics were mostly influenced by the fish species*river types simultaneous effect rather than fish species*fish sex interactions. If there is an interaction, it means that one factor alters the effect of another factor. On the other hand, if there is no interaction, then the difference in the trait value between the groups will be the same in both environments. At this point, river types*fish sex interaction did not influence phenotypic traits. The research also revealed an absence of sexual difference in *C. guineensis* with respect to the phenotypic characteristics that were influenced by the fish species*fish sex interaction. Previous reports have revealed the existence of moderate morphometric and meristic variation in this species (Ukenye et al. 2019). The present study emphasizes the importance of the conservation of tilapia resources in the coastal systems. There is very little data on phenotypic correlations between phenotypic characteristics in *C. guineensis*. A recent study showed that among thirteen morphometric variables, pre-anal length and standard length were the most correlated ($r = 0.96$; $p < 0.01$) (Ukenye et al. 2015). Nevertheless, our study revealed that phenotype traits are not independent factors.

In Benin coastal areas, the use of less selective cross-lake fish traps is very detrimental for species survival. It resulted in a significant reduction of fisheries abundance in water bodies since both small-bodied and large-bodied fish become very scarce in the fisheries. The over-exploitation of the aquatic resources reduces the size of the first sexual maturation. The resulting effects include reduced-fishers' incomes and exacerbated food insecurity, which results in human malnutrition. The typological analysis of the tilapia populations helped identify conservation areas for each species. This is an important step since there is a need to create "enabling environment" for coastal regions' fisheries resources through strategies of protection and rehabilitation. To achieve this, it is essential to strike a balance between the need for development/growth and the need for ecosystem conservation (Bartley and Casal 1998). Furthermore, African countries currently lack the capacity to prevent the escape of non-endogenous selectively-bred fish from aquaculture facilities or to prevent the intentional release of these fish into the wild (Ansah et al. 2014). In Benin, the various fish introductions focused on both indigenous and non-native species (Amoussou et al. 2017). Much participatory management and conservation strategies have been suggested: (i) strengthening and reinforcing regulation about fishery activities; (ii) encouraging the restoring-aquaculture of species; (iii) increasing the number of sanctuaries/classified areas; (iv) developing an environmental monitoring programme; (v) developing ecological sound ecotourism; and (vi) developing an integrated environmental education programme (Teka and Vogt 2010, Adite et al. 2013).

Conclusions

This work gives important evidence to move towards more integrated management of tilapia resources in the coastal areas in Benin in the context of salinization. In response to the increasing level of water salinity, this work attempts to give a step towards the conservation of *C. guineensis* in the lagoon and estuary systems. The salinity of the coastal lagoons is mainly due to the toxic effects of anthropogenic pollution, compared to the SSS. The study provided data sets that may have essential impacts on the development of management and conservation strategies and the utilization of lagoon systems' aquatic genetic resources. The study also provides proof of concept of choosing right populations for the conservation areas identified.

Acknowledgments: The authors thank the fishing rural communities for their great collaboration. This work was financially supported by the International Foundation for Science (IFS), Stockholm, Sweden [grant number A/5861-1].

Conflicts of Interest: The authors declare no conflict of interest.

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