ESJ Natural/Life/Medical Sciences

Study of the Population Variability of Two Chrysichthys Species in Six Aquatic Ecosystems in Côte d'Ivoire

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Doi:10.19044/esj.2023.v19n30p254

Submitted: 20 June 2023
Accepted: 19 October 2023
Published: 31 October 2023

Cite As:
Coulibaly T.A.S. & Adepo-Gourene A.B. (2023). *Study of the Population Variability of Two Chrysichthys Species in Six Aquatic Ecosystems in Côte d'Ivoire*. European Scientific Journal, ESJ, 19 (30), 254. https://doi.org/10.19044/esj.2023.v19n30p254

Abstract

In Côte d'Ivoire, the genus Chrysichthys are subject to intense exploitation pressure and may be threatened by overfishing. The establishment of a sustainable management program for this resource requires in-depth knowledge of this fish. The population relationships were determined by evaluating the morphological variability of the two species of the subgenus Chrysichthys, which was identified in six rivers. Forty-one morphological measurements were carried out on 167 specimens of the species C. maurus and 160 specimens of the species C. nigrodigitatus. These descriptors were subjected to discriminant factor analysis and classification analysis. Within the C. maurus species, specimens from the Bia River and the Aby Lagoon show few morphological differences. These two populations are distinct from the Ebrié Lagoon and the Bandama River. Specimens of the species C. nigrodigitatus can be divided into three distinct groups. The Bia River population occupies an intermediate position between the lot formed by the Agneby River and the Ebrié Lagoon populations and the lot formed by the Bandama River, the Aby Lagoon, and the Grand-Lahou Lagoon populations. Within each lot, the specimens show a great morphological resemblance (similarity). The similarities of the subgenus Chrysichthys could be explained

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

by a potential capacity for exchange of individuals between rivers. The differences between populations would indicate the probable existence of phenotypic plasticity linked to their environment.

Keywords: Côte d'Ivoire, Chrysichthys, Variability, Population, Morphometrics

1. Introduction

The *Claroteidae* family includes African and Asian freshwater and brackish forms. Out of the twelve genera belonging to this family, *Auchenoglanis* and *Chrysichthys are the only* two represented in Côte d'Ivoire (DagetandIltis, 1965). The genus *Chrysichthys*, commonly known as "machoiron", are widely distributed in the fresh and brackish waters of Côte d'Ivoire. This fish, which is highly prized by the local population, is subject to intense exploitation pressure. Bédia *et al.* (2017) highlighted the state of overexploitation of *Chrysichthysnigrodigitatus* in the Ebrié Lagoon. To avoid stock collapse and to preserve biodiversity, sustainable management measures for aquatic ecosystems must be introduced and implemented. However, before a conservation program can be implemented, it is necessary to acquire knowledge about the diversity of species and the dynamics of the populations that colonize these environments. To obtain information on the *Chrysichthys* genus, research has identified four species in the Ivorian hydro-systems sampled (Ouattara, 2019). The aim of this study is to investigate the intra-specific variability of C. nigrodigitatus and C. maurus in order to establish the relationships between populations in six rivers.

1. Material and Methods

2. Study Area

The genus *Chrysichthys* were sampled from east to west in six hydro-systems, namely: the Bia River, the Aby Lagoon, the Ebrié Lagoon, the Agneby River, the Bandama River, and the Grand-Lahou Lagoon (Figure 1).

The Bia River is located between latitudes 5° and 7° 5' north and longitudes 2° 6' and 3° 3' west. Its headwater is in Ghana (Girard *et al*., 1971). This river, which flows into the Aby Lagoon in the southeast of Côte d'Ivoire, covers a basin of 9650 km^2 (Vanden-Bossche & Bernacsek, 1990). It is 290 km long, including 120 km in Côte d'Ivoire.

Located in the extreme southeast of Côte d'Ivoire, between 5°05' and 5°22' north latitude and 2°51' and 3°21' west longitude, the Aby Lagoon system forms a natural border between Côte d'Ivoire and Ghana (Chantraine, 1980). This complex covers an area of 424 km^2 and includes the Aby, Tendo, and Ehy Lagoons. The Aby Lagoon is fed with fresh water by the Bia to the

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

northwest and the Tanoé to the east. The south of the Aby sector receives marine water from the Assinie channel (N'Goran, 1995).

The Ebrié Lagoon is located in the south of Côte d'Ivoire. It lies between latitudes 5°02' and 5°42' north and longitudes 3°47' and 5°29' west. With a total surface area of 566 km², the Ebrié Lagoon is approximately 130 km long (Albaret, 1994; Durand & Guiral, 1994). The lagoon is artificially connected to the Grand-Lahou Lagoon in the west by the Assagny canal. It is also connected to the Aby Lagoon in the east by the Assinie canal, as well as the Atlantic Ocean in the center-east by the Vridi canal. At its eastern end, the Ebrié Lagoon is supplied with fresh water by the Comoé river, the Agnéby river, and the Mé river (Laë, 1991).

The Agnéby river is located in Côte d'Ivoire between 5°-7°N and 4°-5°W. It flows through the forest zone and is around 200 km long, with a catchment area of 8600 km^2 (Diomandé *et al.*, 2009).

The Bandama basin is located within Côte d'Ivoire between latitudes 5° and 10°20' North and longitudes 3°50' and 7° West. It covers an area of 97,500 km^2 and is 1,050 km long (Lévêque *et al.*, 1983).

Covering an area of around 192 km^2, the Grand-Lahou Lagoon system is in the southern part of Côte d'Ivoire between latitudes 5°07' and 5°14' North and longitudes 4° and 5°25' West (Durand & Skubich, 1982).

The sampling sites were selected based on the ease of access and availability of fish.

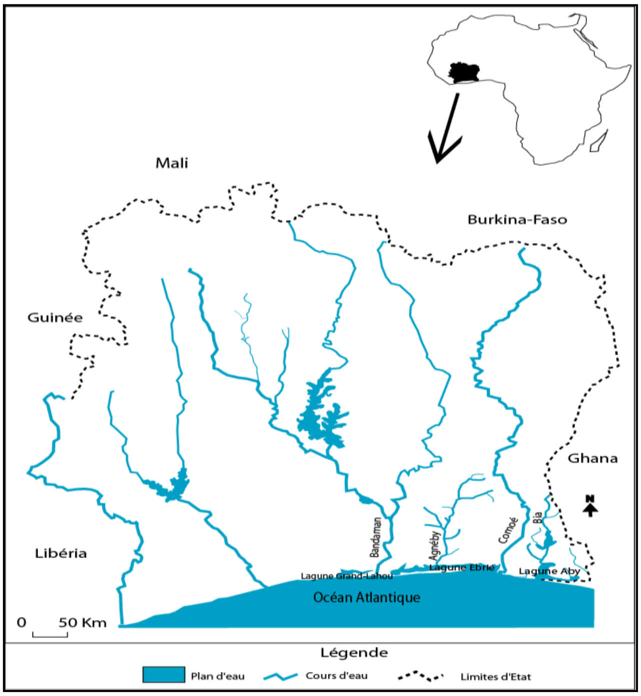

Figure 1. Sampling Sites for *Chrysichthys* Fish

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3. Fish Sampling

The interspecific morphological analysis included 167 specimens of the species *C. maurus* and 160 specimens of the species *C. nigrodigitatus*. The fish were obtained from the sampling campaign that took place from 2012 to 2014. For each fish, 41 measurements were taken (Figure 2). Since the age of the fish was not determined, the measurements were standardized to avoid size variations due to age differences between individuals. Therefore, all measurements expressed in millimeters were converted into a percentage of the standard length. However, head measurement was expressed as a percentage of the length of the headtête (Mayr, 1970; Thys van den Audenaerde, 1970; Teugels, 1986).

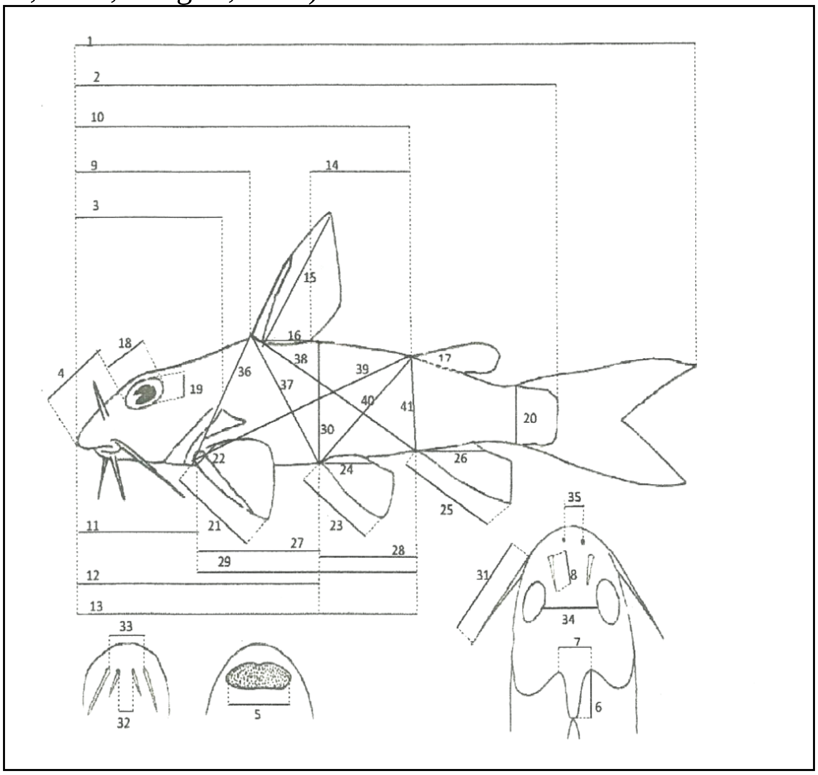

Figure 2. Metrics Measurements Taken from the Individuals of the Four Species of Chrysichthys

1. total length (TL); 2. standard length (SL); 3. head length (HL); 4. snout length (SnL); 5. width of premaxillary toothplate (WPm T); 6. occipital process length (OPL); 7. occipital process width (OPW); 8. nasal barbel length (NBL); 9.predorsal length (DsL); 10. preadipose length (AdL); 11. prepectoral length (PtL); 12. prepelvic length (PlL); 13. preanal length (AnL); 14. distance between dorsal and adipose fins (DDsAd); 15. dorsal fin height (DsH); 16. dorsal base (DsB); 17. adipose base (AdB); 18. eye diameter horizontal (ED1); 19. eye diameter vertical (ED2); 20. caudal peduncle length (CPcL); 21. pectoral height (PtH); 22. pectoral base (PtB); 23. pelvic height (PlH); 24. pelvic base (PlB); 25. anal height (AnH); 26. anal base (AnB); 27. distance pectoral/pelvic (DPtPl); 28. distance pelvic/anal (DPlAn);

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29. distance pectoral/anal (DPtAn); 30. body height (BdH); 31. mandible barbell length 1 (MBlL1); 32. mandible barbell length 2 (MBlL2); 33. mandible barbell length 3 (MBlL3); 34. distance inter-orbital (DIO); 35. distance inter-nostril (DIN); 36. distance pectoral/dorsal (DPtDs); 37. distance pelvic/dorsal (DPlDs); 38. distance anal/dorsal (DAnDs); 39. distance pectoral/adipose (DPtAd); 40. distance pelvic/adipose (DPlAd); 41. distance anal/adipose (DAnAd).

2.3. Statistical Analysis

Discriminant Factor Analysis (DFA) was used to test the effectiveness of the characters in predicting different species location. For this analysis, a stepwise inclusion procedure was carried out to reduce the number of characters accordingly and to identify the combinations of characters that best separate species (Jain *et al.*, 2000; Poulet *et al.*, 2004). The percentage of correct classification of individuals is determined to assess the effectiveness of the discriminant analysis (Silva, 2003; Tomovíc & Džukíc, 2003; Marques *et al.*, 2006). Hierarchical Cluster Analysis (HCA), based on Mahalanobis distance matrices obtained by DFA, was used to evaluate population relationships. The hierarchical clustering process was represented as a dendrogram, where the tree illustrated each step in the clustering process. Furthermore, the minimum variance clustering method or Ward's method was used with the Euclidean distances. All treatments were performed using the program STATISTICA (StatSoft, version 7.1).

4. Results

5. Morphological Diversity of *Chrysichthysmaurus* Populations

The analysis focused on 167 specimens of the species *Chrysichthys maurus*. 25 samples were taken from the Bia River, 34 from the Aby Lagoon, 35 from the Ebrié Lagoon, and 73 from the Bandama River.

3.1.1. Discriminant Factor Analysis of Populations

The metric variables were subjected to an analysis of variance. Amongst these descriptors, 31 varied significantly between the *C. maurus* populations. Thus, they are subjected to Wilk's Lambda test of bottom-up stepwise discriminant factor analysis. 18 characters were identified by the test and the following nine descriptors were retained: DsH, AdB, OPW, AnL, PtB, DAnAd, NBL, OPL, and DDsAd. Significantly, these descriptors have a highly significant level of discrimination ($p < 0.001$) (Table 1).

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Table 1. Multivariate Wilk's Lambda (λ) Significance Tests of Metric Variables in the Populations of the Species *Chrysichthysmaurus*

Variables	λ	F	p
DsH	0,70	20,75	***
AdB	0,78	14,16	***
OPW	0,82	10,80	***
AnL	0,82	10,50	***
PtB	0,86	8,15	***
DAnAd	0,87	7,00	***
NBL	0,88	6,7	***
OPL	0,88	6,37	***
DDsAd	0,89	6,00	***
OPcL	0,90	5,53	**
PtH	0,91	4,93	**
DIO	0,92	4,49	**
AdL	0,92	4,48	**
WPmT	0,92	4,34	**
ED1	0,93	3,91	*
DPtDs	0,93	3,6	*
AnH	0,93	3,42	*
DIN	0,94	3,2	*

Discriminant Factor Analysis showed an overall correct classification rate of 95.21% (Table 2). Individuals from the Ebrié Lagoon were correctly classified at 97.14%. However, only one individual was assigned to the Bia population. The majority of the Bia specimens (80%) were correctly assigned to their group of origin. Subsequently, only five specimens from this population were assigned to the Aby Lagoon. The percentages of correct classification of specimens from Aby Lagoon and Grand-Lahou Lagoon are 79.41% and 85.71%, respectively. As for the specimens from the Bandama population, their membership to their origin group was confirmed at 100% by the Factorial Discriminant Analysis.

Table 2. Matrix for Classification of Specimens of the Species *Chrysichthys Maurus* by DFA

	Correct %	Ebr	Bad	Bia	Aby
Ebr	97.14	34	0	0	1
Bad	100	0	73	0	0
Bia	84	0	0	21	4
Aby	91.18	0	0	3	31
Total	95.21	34	73	24	36

Ebr: Ebrié, Bad: Bandama

Figure 3 shows the distribution of populations in the canonical 1 and 2 planes of the Discriminant Factor Analysis. On the graph, the Bandama and Ebrié Lagoon populations are clearly differentiated from the others, while the

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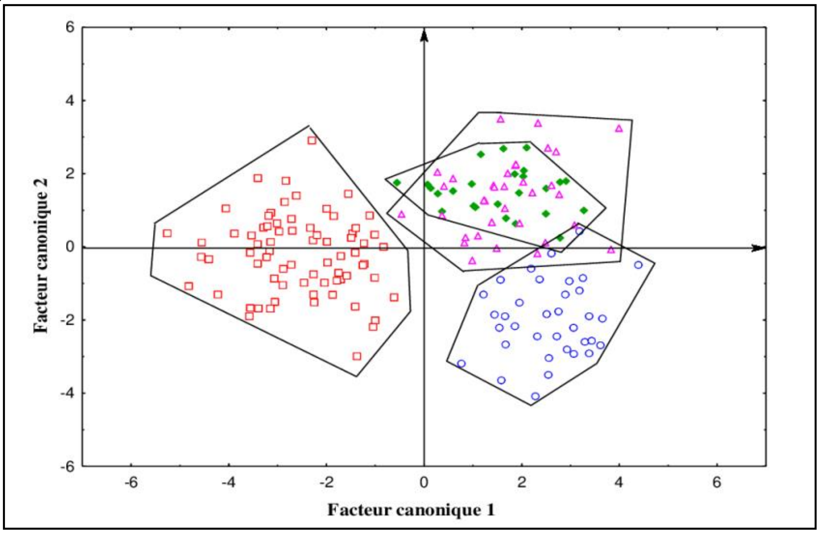
scatter plots representing the Bia River and Aby Lagoon populations overlap entirely.



Bandama Ebrié Aby Bia

Figure 3. Projection of *C. Maurus*populations in the Canonical 1 x 2 Plane of the Discriminant Factor Analysis of Metric Data

3.1.2. Hierarchical Cluster Analysis of the Populations

The different populations are grouped according to the Hierarchical Classification Analysis, and the results are presented in Figure 4. At Euclidean distance of 20, three distinct batches emerge. Batch I is formed by the population of the Ebrié Lagoon, while Batch II is formed by the populations of the Bia River. On the other hand, the Aby Lagoon and Batch III is represented by the population of the Bandama River.

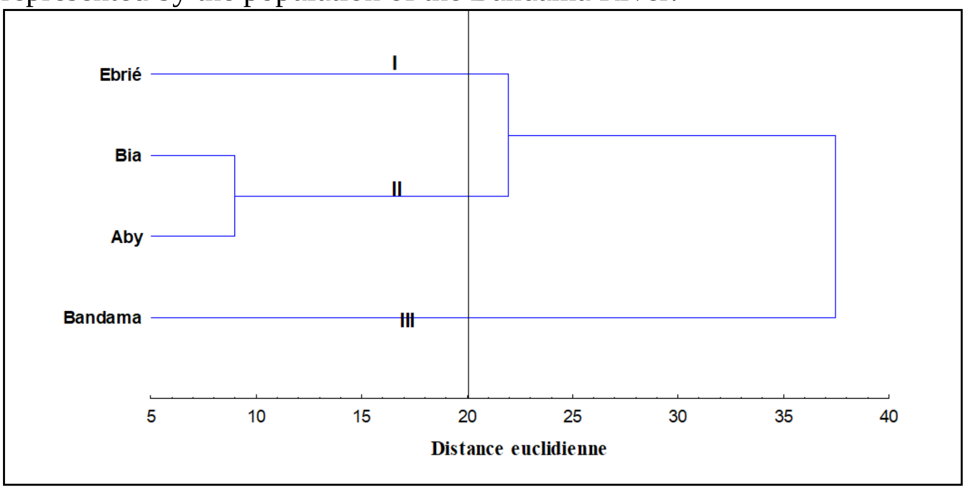


Figure 4. Dendrogram Showing Morphometric Similarities Between Populations of the Species *Chrysichthys Maurus*

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6. Morphological Diversity of *C. nigrodigitatus* Populations

The sample of the species *C. nigrodigitatus* is composed of 160 specimens. 15 were collected in the Bia River, 47 in the Ebrié Lagoon, 11 in the Agneby River, 50 in the Aby Lagoon, 20 in the Bandama River, and 17 in the Grand-Lahou Lagoon.

3.2.1. Discriminant Factor Analysis of Populations

The results of the bottom-up stepwise factor analysis are shown in Table 3. The nine descriptors (DPlDs, DAnAd, HL, LBlM1, WPmT, DDsAd, DIO, NBlL, BdH) contribute strongly to the discrimination of the different populations ($p < 0.001$).

Table 3. Multivariate Wilk's Lambda (λ) Significance Tests of Metric Variables in the Populations of the Species *Chrysichthys Nigrodigitatus*

Variables	λ	F	p
DPlDs	0,73	10,27	***
DAnAd	0,76	8,79	***
HL	0,77	8,24	***
LBlM1	0,77	8,04	***
WPmT	0,81	6,57	***
DDsAd	0,82	6,14	***
DIO	0,82	6,14	***
NBlL	0,83	5,41	***
BdH	0,86	4,54	***
PtB	0,88	3,81	**
LBlM2	0,88	3,72	**
AdB	0,89	3,46	**
DPtAn	0,90	3,07	*
DIN	0,90	3,02	*
DPtPl	0,90	2,96	*
DsL	0,91	2,85	*
AnH	0,91	2,54	*
PlH	0,92	2,50	*
PtH	0,92	2,46	*

Figure 5 shows the distribution of populations along the canonical axes 1 and 2 of the DFA. The scatter plot representing the Bia River population is clearly different from the others. The populations of the Aby, Grand-Lahou, and Bandama Lagoons overlap and are located in the negative sector of canonical axis 1. However, the scatter plots representing the taxa of the Agneby River and the Ebrié Lagoon overlap in the positive sector of canonical axis 1.

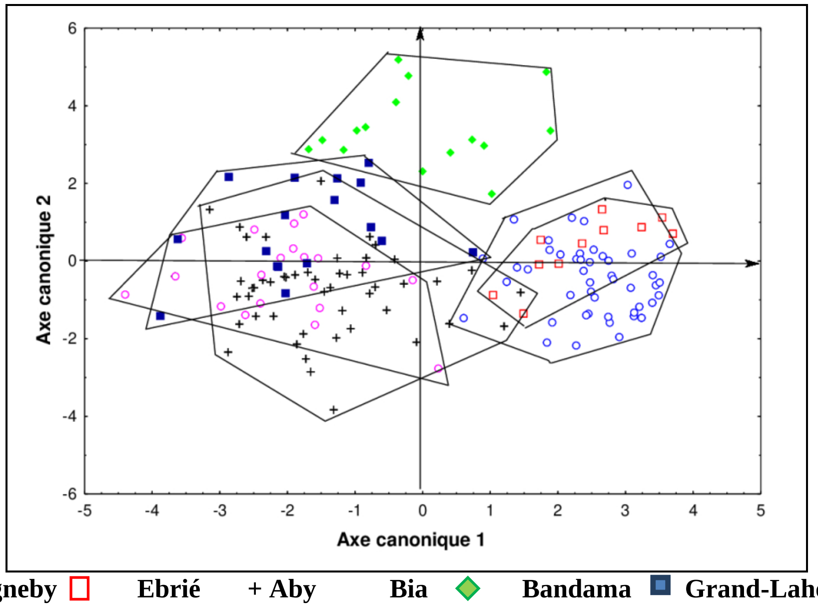

Figure 5. Projection of the Populations of *C. Nigrodigitatus* in the Plane Formed by the Canonical Axis 1 and 2

The classification matrix confirms that 91.25% of the specimens belong to their group of origin (Table 4). The correct classification rate is 100% for the Bia River, 93.62% for the Ebrié Lagoon, 92% for the Aby Lagoon, 90% for the Bandama River, 88.24% for the Grand-Lahou Lagoon, and 72.73% for the Agneby River.

Table 4. Matrix for Classification of Specimens of the Species *Chrysichthysnigrodigitatus* by DFA

	Correct percentage	Ebr	Agb	Bia	Aby	Bad	GL
Ebr	93.62	44	2	0	1	0	0
Agb	72.73	3	8	0	0	0	0
Bia	100	0	0	15	0	0	0
Aby	92	1	0	0	46	1	2
Bad	90	0	0	0	2	18	0
GL	88.24	0	0	0	0	2	15
Total	91.25	48	10	15	49	21	17

Ebr: Ebrié, Agb: Agneby, Bad: Bandama, GL: Grand-Lahou

3.2.2. Hierarchical Cluster Analysis of the Populations

Through Hierarchical Cluster Analysis, the populations were divided into three distinct groups, with an aggregation distance of 20 (Figure 6). Group I consist of the populations of the Agneby River and the Ebrié Lagoon, which are morphometrically close. Group II consist of the Bia River population

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which is in an intermediate position. The populations of the Aby Lagoon, the Grand-Lahou Lagoon, and the Bandama River form group III and are close to each other.

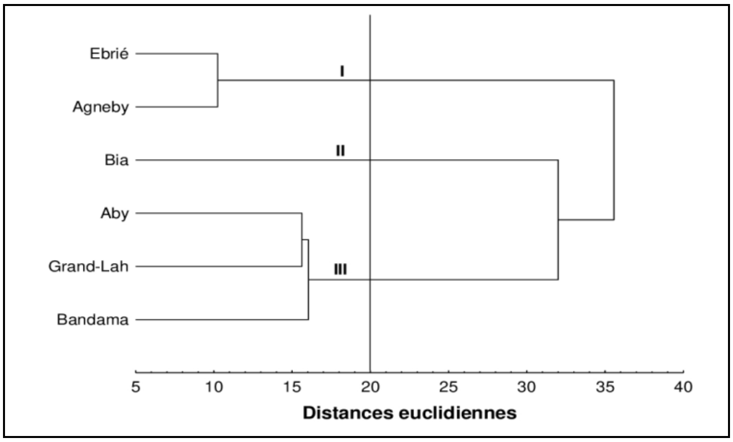

Figure 6. Dendrogram Illustrating the Morphological Variability of *C. Nigrodigitatus* Populations Based on Metric Descriptors

7. Discussion

For the species *C. maurus*, the results of the study based on the populations of the rivers sampled made it possible to detect more or less significant morphological differences between the populations. Specimens from the Bandama River are characterized by small eyes and wide nostrils, a large adipose fin, a long dorsal fin that reaches or exceeds the adipose fin, large pelvic, and pectoral fins when folded. Specimens from other rivers sampled are characterized by a small dorsal fin, a small adipose fin, and small pectoral and pelvic fins. In addition, specimens from the Ebrié Lagoon are distinguished by small eyes and wide nostrils. However, those from the Bia River are distinguished by small eyes and close nostrils, while those from the Aby Lagoon have large eyes and close nostrils. All these morphological differences suggest the possible existence of phenotypic plasticity. Ferrito *et al*. (2007) reported that habitat differences affect the morphology differently in several populations. Discriminant Factor Analysis shows that the Aby and Bia populations show strong morphological similarity, while the Ebrié Lagoon and Bandama River populations are distinct. Furthermore, the hierarchical classification indicates that the first two populations are closer to the Ebrié Lagoon population than the Bandama River population. The phenotypic similarity between specimens from the Bia River and the Aby Lagoon, including their morphological affinities with specimens from the Ebrié Lagoon, could be due to the fact that these three rivers are connected to each other. In addition, the Aby Lagoon is directly fed with fresh water by the Bia River. To facilitate navigation, the Aby Lagoon and the Ebrié Lagoon were connected by the Assinie canal, which was built between 1955 and 1957

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

(Kouassi, 2010**)**. Therefore, specimens can probably migrate over long distances, which implies an exchange of individuals between the rivers. Thus, the potential capacity of populations to evolve as independent biological entities is limited by the exchange of individuals between populations (Cheng *et al*., 2005). The morphological similarity between the populations could also be due to the fact that the Aby Lagoon, the Ebrié Lagoon, and the Bia River are subject to the same physico-chemical parameters. The results of the analyses showed that the Bandama River population is morphologically isolated from the other populations. This isolation is manifested in this taxon by a major morphological particularity. Interestingly, the long filament on the dorsal fin reaches or exceeds the adipose fin when folded. This particularity was observed by Risch (1992) during his research on fish from the same river. This morphological difference is due to the adaptation of the specimens to different environmental conditions. Nonetheless, the Bandama River is subject to several climatic regimes (tropical and equatorial). According to Paugy and Lévêque (1999), populations of the same species, living in different geographical areas, can be morphologically different. In addition, the Grand-Lahou Lagoon provides connectivity between the Bandama River and the Ebrié Lagoon. Fish from this river have a filament on the dorsal fin that is smaller than the Bandama specimens and longer than the Ebrié Lagoon specimens. According to Turan (2004), a sufficient degree of isolation can result in significant phenotypic differentiation among fish populations of a species.

For the species *C. nigrodigitatus*, the results of the intra-population study showed low values of the coefficient of variation based on the populations of the Ebrié Lagoon and the Agneby River. This low morphological variation could be explained by a phenotypic homogeneity linked to the low variations in environmental conditions. The analysis of variance made it possible to highlight the differences between the populations of the rivers sampled. Specimens from the Bia River are characterized by long head, large eyes, and long pectoral fins. Conversely, those from the Bandama River have a moderately elongated head, large eyes, and long pectoral fins. The Grand-Lahou Lagoon population is distinguished by an elongated head, large eyes, and short pectoral fins. Specimens from the Aby Lagoon are distinguished by short head, large eyes, and long pectoral fins. Specimens from the Agneby River have short head, small eyes, and small pectoral fins. Specimens from the Ebrié Lagoon are characterized by short head, small eyes, and small pectoral fins. In contrast to the *C. maurus* species, the populations of the *C. nigrodigitatus* species differ in few variables. On the one hand, the population in the Agneby River is similar to the Ebrié Lagoon. On the other hand, the populations of the Bandama River, the Aby Lagoon, and the Grand-Lahou Lagoon show a high similarity due to the overlap of morphometric

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

descriptors. The Bia River population occupies the intermediate position. The phenotypic similarities between the Agneby and Ebrié Lagoon populations is due to the similar environmental variations. Certainly, the swampy area in which the Layo station is located (on the Ebrié lagoon) has a hydroclimate, which is strongly influenced by the flooding of the Agneby forest river (Durand et al., Guiral, 1994). In addition, the absence of a geographical barrier between these two rivers probably leads to an exchange of individuals between the populations. The few morphological differences observed at the level of the relatively "homogeneous" populations is related to certain environmental parameters. This variability is due to phenotypic plasticity in relation to the environmental factors of each river. Therefore, these populations would be ecological variants or ecotypes (Dkhil-Abbes & Kraïem, 2011).

Conclusion

The results of the study based on the populations of the sample rivers made it possible to detect more or less significant morphological differences between the populations. Within the *Chrysichthys maurus* species, the populations of the Bia River and the Aby Lagoon show much greater morphological affinities. The morphological isolation of the Bandama specimens is marked by the presence of a long filament on their dorsal fin. Populations of the *Chrysichthys nigrodigitatus* species have been divided into six morphologically distinct groups: the Bia River population, the Ebrié Lagoon, Agneby river population, the Aby Lagoon, Grand-Lahou Lagoon, and Bandama River population. Finally, the morphological differences indicate the possible existence of phenotypic plasticity in the populations. On the other hand, the similarities can be explained by the fact that the potential capacity of populations to evolve as independent biological entities is limited by the exchange of individuals between the populations. The molecular analyses associated with these morphological analyses will help to clarify the relationships between the different populations.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All of the data are included in the content of the paper.

Funding Statement: This study is part of the research programme of the Aquaculture Department of the Oceanological Research Center.

Animal Studies: Fish were purchased from fishermen in the villages along each river and ethical guidelines were followed.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

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 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

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