Geometric Morphometric Analysis of *Channa striata* (Striped Snakehead) Populations from Laguna de Bay, Philippines Reveals Shape Differences in Relation to Water Quality

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ABSTRACT

Channa striata, locally known as dalag, constitute a major aquaculture resource in Laguna de Bay. Owing to its popularity as a food source, threats such as overfishing may potentially place this species at risk. However, studies regarding its status within the lake is lacking. One way to address this gap is through population studies using geometric morphometrics. In this study, a total of 82 specimens were collected across three areas of the lake, namely, Binangonan, Calamba, and Tanay. These areas were assessed using secondary data for physicochemical parameters, which revealed significantly higher ammonium-nitrogen levels in Binangonan compared to the other areas. Geometric morphometrics was then used to determine whether shape variation existed among *C. striata* populations. Results showed that shape variation was greatest in the cranial region, with fish from Binangonan and Tanay having the greatest variation in shape. On the other hand, specimens from Calamba had the highest morphometric values. Lastly, these findings were then correlated with water quality data using Canonical Correlation Analysis. Results indicated that shape variation in the cranial region was correlated with differences in dissolved oxygen and pH content of the lake. The weight and length of fish were inversely correlated to the levels of ammonium-nitrogen and total dissolved solids, with specimens from Binangonan displaying a high sensitivity to ammonium-nitrogen.

Keywords: dalag, freshwater fish, shape variation, Laguna Lake, physicochemical parameters

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INTRODUCTION

Laguna de Bay, located at the eastern part of Metro Manila, Philippines, is the largest lake in the country, with a surface area of 900 km^2 and an average depth of 2.5 m (LLDA 2016). The lake is one of the top producers of freshwater fish, providing a source of food and income and contributing heavily to the economic growth of the country (Cuvin-Aralar 1990; Aquino et al. 2011). Among the fishes present in the lake are introduced cultured species (milkfish *Chanos chanos*, bighead carp *Aristichthys nobilis*, Tra catfish *Pangasianodon hypophthalmus* and Nile tilapia *Oreochromis niloticus*), native and other species (silvery theraponid *Leiopotherapon plumbeus*, Manila sea catfish *Arius manillensis*, gobies *Glossogobius giuris, Giuris margaritacea*, and striped snakehead *Channa striata*) (Cuvin-Aralar 2016).

However, despite the management plans and policies implemented for the lake, a decrease in fish catch (Tamayo-Zarafalla et al. 2002) as well as recent fish kills (Angeles 2019; Cinco 2020) were noted to have been occurring at the lake. Various factors can be attributed to these events, such as overfishing, intensive aquaculture (Santos-Borja and Nepomuceno 2006), illegal use of destructive fishing gear (i.e., spear and drag seine) (Palma et al. 2002), rapid land use, and water pollution (e.g., organic waste, solid waste) (Kosmehl et al. 2008). These problems pose harm to the biodiversity in the area while also negatively affecting local aquaculture enterprises.

Among the economically important fish species with an observed decline in catch data is the dalag (*Channa striata*). *C. striata*, commonly known as striped snakehead, is regarded to be of high economic value in the country as it contributed a total value production cost of 1,043,474.86 Philippine pesos in 2015, placing this species at the third spot among species contributing to inland water capture production (PSA 2018). It is a popular fish due to its high-quality meat, low-fat content, few intramuscular spines, tasty flavor, and relatively cheaper price compared to other fishes (Song et al. 2013). Perhaps due to the increasing demand for the species, a decline in *C. striata* catch data was noted by the Bureau of Agricultural Statistics (2012; 2015; 2018; 2019) from 10,469.58 metric tons in 2010 to 9,512.3 metric tons in 2017, or an average decline of 7% in nine years. Given the high value of this fish, especially as a top target fish that is prone to overfishing and population decline, it is imperative to study their population.

One way to manage and assess the population of this fish is through phenotypic variation using morphometric identification. Changes in the growth and development of a fish often creates a difference in body shape within a species and may be influenced by the interplay among the environment, genetics, and selection on the life history of a species (Cadrin 2000). A widely used method to study shape variation is geometric morphometrics (GM) (Santos and Quilang 2012), which is unlike traditional morphometric tools that make use of linear measurements, counts, and ratios (Adams et al. 2004) to differentiate between populations. Landmark points of a species, which are defined as the anatomical points in the species (Richtsmeier et al. 2002), are commonly used in GM. Santos and Quilang (2012) studied populations of catfish (*Arius manillensis and Arius dispar*) in Laguna de Bay that were observed to be in decline likely due to local overfishing. In their study, the left side body and dorsal head view of the two species were subjected to GM analysis, which revealed that most of the shape variation came from body size rather than the dorsal head of the fish, which suggests influence by various factors such as species diet, movement, and habitat.

The objective of the study was to examine the shape variation between populations of *C. striata* found in Laguna de Bay, specifically in the northwest, south, and central regions of the lake, using GM which can be used to provide information regarding the current condition of *C. striata* in the lake. The different areas within the lake were chosen according to the differences in land use, specifically: the northwest bay (Binangonan), which is the closest bay to Metro Manila and is surrounded by highly urbanized communities, industrialized sites, and ports for small boats; the south bay (Calamba), which is mostly surrounded by residential areas; and the central bay (Tanay), which is mainly surrounded by agricultural areas and farmland (Johnson and Iizuka 2015). Likewise, these areas were the major landing sites (Rizal and Laguna) for *C. striata* found in Laguna de Bay (BAS 2018). In addition, water quality conditions in these three areas, using the physicochemical parameters measured by the Laguna Lake Development Authority, were assessed to know whether a significant change in the physicochemical parameters happened in the lake. The correlation between the shape variation found in *C. striata* and possible changes in physicochemical parameters were also investigated. This information can be used to reveal whether certain selective pressures within the area could favor certain phenotypic structures that could result in different morphotypes of *C. striata*.

MATERIALS AND METHODS

Specimen collection

Channa striata specimens were obtained from Binangonan (14°27’47.36” N, 121°11’34.98” E), Calamba (14°12’38.93” N, 121°09’53.15” E), and Tanay (14°29’33.79” N, 121°17’17.54” E) areas of Laguna de Bay (Figure 1). A total of 82 fish specimens were collected on 20 January 2018 and 17 March 2018 through the help of local fishermen around the lake. Specifically, 30 specimens from Binangonan, 27 specimens from Calamba, and 25 specimens from Tanay were collected. The fishing gear used to collect the specimens were a combination of a fish shelter set at the lake bottom that served as an aggregating site and a manual seine to catch the fish (locally called takibo) (Palma et al. 2002; 2017 personal communication with fishermen in the sampling areas). Across the three areas, the same set of fishing gear (takibo) was used by the fishermen. In addition, the total weight and length measurements (total length, body depth, and pectoral length) were measured using a weighing scale and metric ruler, respectively.

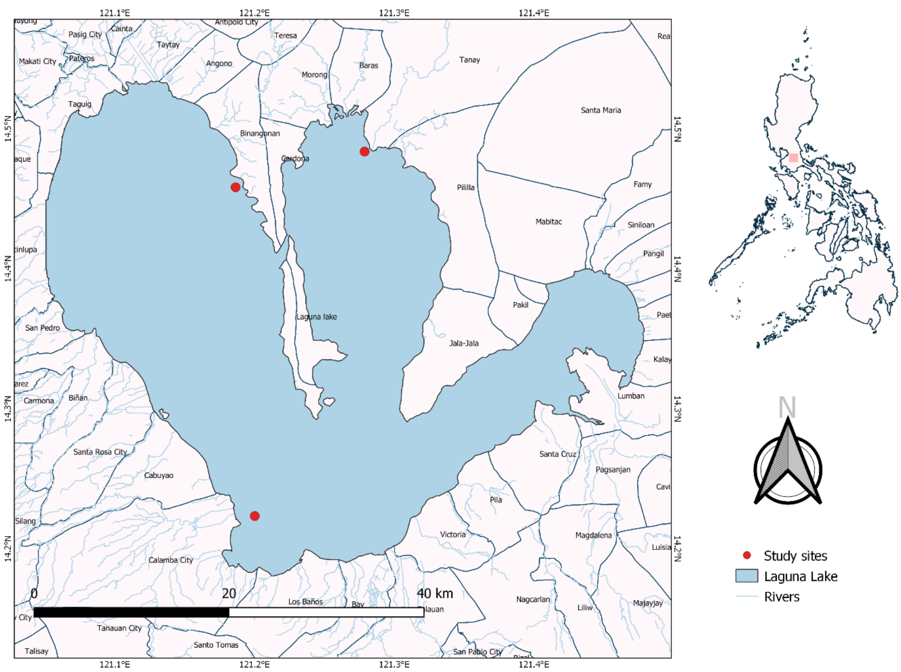

Figure 1. Map of Laguna de Bay showing the three sampling areas in Binangonan, Calamba, and Tanay.

Water quality data

The following water quality data were obtained from the Laguna Lake Development Authority (LLDA): water temperature (in °C) and total dissolved solids (TDS) (in mg/L) (from 2013-2016), dissolved oxygen (DO) (in mg/L) and pH (from 2015-2017), and ammonium-nitrogen (in mg/L) and nitrate-nitrogen (mg/L) (from 2016-2017). Each data on physicochemical parameters was specific among the three sites. The DO, pH, ammonium-nitrogen, and nitrate-nitrogen of the lake were measured monthly, while the temperature and TDS were measured yearly.

Analysis on length, weight, condition factor, and water quality data

The condition factor of each specimen, which was calculated by dividing the total weight (in grams) by the cube of the total length (in centimeters) and multiplying the quotient by 100, was recorded. Next, the weight and length measurements, as well as the condition factor, were subjected to one-way Analysis of Variance (ANOVA) with post-hoc tests (Tukey's HSD) using the IBM SPSS Statistics version 26 (IBM Corporation2019). Similarly, the water quality data across the three sampling sites were subjected to one-way ANOVA followed by post-hoc tests (Tukey's HSD) using the IBM SPSS Statistics version 26 (IBM Corporation2019). These tests were used to detect the differences in specimen morphometry and physicochemical parameters across the three sampling sites. Likewise, the condition factor was used to assess the well-being and degree of fatness of the fish (Zelditch et al. 2004).

Geometric morphometrics and data analysis

The left side body of each specimen was pinned in place on a white background with a standard metric ruler at the bottom in order to provide scale. Each specimen was photographed using a Canon EOS 700D DSLR Camera. The ten landmarks, serving as anatomical points, chosen for this study were based on those used by Song et al. (2013), namely: (1) anterior tip of the snout; (2) posterior aspect of the neurocranium; (3) origin of dorsal fin; (4) insertion of dorsal fin; (5) anterior attachment of dorsal membrane from caudal fin; (6) posterior end of vertebrae column; (7) insertion of anal fin; (8) original of anal fin; (9) origin of pelvic fin; and (10) posterior end of lower jaw (Figure 2). The landmarks were plotted digitally on each image using the tpsDig2 software (Rohlf 2010). The raw landmark coordinates were superimposed as shape variables using the CoordGen8 software through the Generalized Procrustes Analysis (GPA). GPA was used to ensure that differences in shape would be independent of size, position, or orientation of the fish (Slice 2007) and to check for possible outliers (Sotola et al. 2019). The corrected coordinates generated from GPA were used for subsequent analysis. The centroid size, which is the square root of the sum of squared distances of the landmarks in a configuration to the average location (Slice 2007), of each specimen was calculated using the CoordGe8 software.

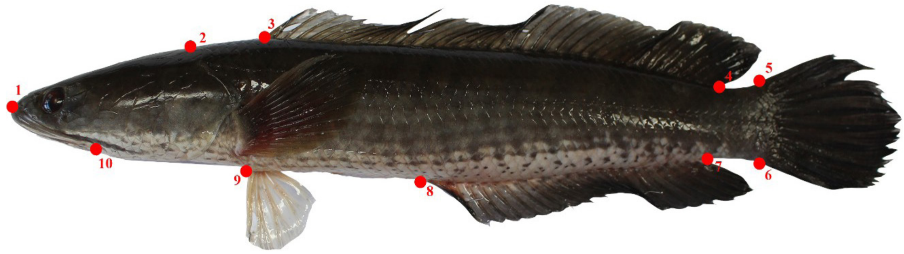

Figure 2. Landmarks of *C. striata* used in the study: (1) anterior tip of the snout; (2) posterior aspect of the neurocranium; (3) origin of dorsal fin; (4) insertion of dorsal fin; (5) anterior attachment of dorsal membrane from caudal fin; (6) posterior end of vertebrae column; (7) insertion of anal fin; (8) origin of anal fin; (9) origin of pelvic fin; and (10) posterior end of lower jaw.

Principal Component Analysis (PCA) was performed using the PCAGen8 software to examine overall shape variability among all specimens collected from the three localities. To test whether the observed shape variations were not dependent on the size of each specimen, Multivariate Analysis of Covariance (MANCOVA) was performed using IBM SPSS Statistics version 26 (IBM Corporation 2019). In this test, the CV 1 and CV 2 scores were treated as the dependent variable, the standard length as the covariate, and the study sites as the fixed factor (Zelditch et al. 2004). To further validate the results of MANCOVA, regression of the PC 1 scores on the logarithm of the centroid size was performed to determine the growth pattern of *C. striata* using Microsoft® Excel®for Microsoft 365. The MANCOVA and regression analysis were both used to identify whether *C. striata* exhibits isometric or allometric patterns of growth.

Multivariate Analysisof Variance (MANOVA) was performed using the CVAGen8 to differentiate the three localities. Results were summarized using Canonical Variate Analysis (CVA). Deformation grids and vector plots were generated to visualize the shape variation among the population. In addition, pairwise comparisons between populations were conducted using CVAGen8 and TwoGroup 8 software. On the other hand, TwoGroup8 software was used to calculate the Goodall's F-test. MANOVA and Goodall's F-test were performed to detect the differences or similarities among the three populations.

Correlation of morphometric values to water quality data

The correlation between the morphometric values of the *C. striata* populations and the water quality data using the physicochemical parameters measured were examined using Canonical Correlation Analysis (CCA). Separate CCA were used to describe the correlation between fish morphometric values (weight, total length, body depth, and pectoral length) and physicochemical parameters of the lake (total dissolved solids and ammonia content). The other one was done between the 10 anatomical points of the fish and physicochemical parameters of the lake (pH and dissolved oxygen). The canonical variate (CV) scores, canonical correlation coefficients, and Wilk's test of significance were generated through the CCA package of R studio version 1.1.442 (Torres 2020). These data were used to examine whether environmental factors were correlated with the shape variation observed among *C. striata* populations.

RESULTS

Length, weight, and condition factor

The descriptive statistics of the measured weight and length of each specimen from the three sampling sites within Laguna de Bay were summarized in Table 1. The measured parameters were as follows: weight ranged from 76.00 g to 1040.00 g, total fish length ranged from 20.80 cm to 52.10 cm, body depth ranged from 2.90 cm to 7.50 cm, and pectoral fin length ranged from 2.60 cm to 8.20 cm. The calculated condition factor ranged from 0.30 to 1.60, while the calculated centroid size ranged from 22.72 to 53.37. When these measurements were subjected to one-way ANOVA with post hoc tests, it was observed that of the six morphometric variables, only the condition factor (P=0.092) did not differ across the sampling sites (Table 1). Results of the post-hoc tests revealed that the total weight (P=0.003), total length (P=0.001), body depth (P<0.001), and centroid size (P<0.001) of specimens collected from Calamba statistically differ from those obtained in Binangonan and Tanay.

Table 1. Summary (means ± SE, F-values, and *P*-values) of the ANOVAs comparing water quality variables across three areas in Laguna de Bay. DO – dissolved oxygen, TDS – total dissolved solids. Ranking for post hoc tests in cases with significant effects are given. *P*-values <0.05 are in bold print.

Parameter	Binangonan	Calamba	Tanay	F-value	*P*-value	Ranking
Water temp (°C)	28.70 ± 0.08	28.50 ± 0.05	28.20 ± 0.14	2.923	0.105	
DO (mg/L)	8.27 ± 0.40	8.32 ± 0.19	8.80 ± 0.42	0.752	0.474	
pH	8.20 ± 0.08	8.36 ± 0.79	8.40 ± 0.10	1.403	0.251	
TDS (mg/L)	385.25 ± 100.68	352.25 ± 102.90	386.50 ± 128.50	0.030	0.970	
Nitrate-N (mg/L)	0.39 ± 0.11	0.22 ± 0.08	0.22 ± 0.07	1.265	0.289	
Ammonium-N (mg/L)	0.13 ± 0.04	0.04 ± 0.01	0.05 ± 0.01	3.965	**0.024**	Binangonan>(Calamba=Tanay)

Water quality

The summary of data for the physicochemical parameters measured by the Laguna Lake Development Authority were summarized in Table 2. Across the sampling sites, no significant difference was found in water temperature, DO, pH, TDS, and nitrate-nitrogen (Table 2). However, ammonium-nitrogen levels across sampling sites (*P*=0.024) statistically differed, with a higher mean concentration in Binangonan (0.13 mg/L) compared to Calamba and Tanay (Table 2).

Table 2. Summary (means ± SE, F-values, and *P*-values) of the ANOVAs comparing morphometric variables of *C. striata* across the three areas in Laguna de Bay. Ranking for post hoc tests in cases with significant effects are given. *P*-values <0.05 are in bold print.

Morphometric Variable	Binangonan (N=30)	Calamba (N=27)	Tanay (N=25)	F-value	*P*-value	Ranking
Total weight	285.63 ± 25.99	448.63 ± 53.97	294.56 ± 17.25	6.444	**0.003**	**Calamba > (Binangonan =Tanay)**
Total length	30.58 ± 0.94	36.37 ± 1.54	32.43 ± 0.68	7.093	**0.001**	**Calamba > (Binangonan =Tanay)**
Condition factor	0.92 ± 0.01	0.85 ± 0.04	0.85 ± 0.02	2.463	0.092	
Centroid size	31.53 ± 1.00	37.04 ± 1.82	31.43 ± 0.67	6.367	**0.003**	**Calamba > (Binangonan =Tanay)**
Body depth	4.13 ± 0.12	5.10 ± 0.23	4.22 ± 0.06	11.808	**<0.001**	**Calamba > (Binangonan =Tanay)**
Pectoral fin length	4.43 ± 0.14	5.31 ± 0.23	3.93 ± 0.06	15.980	**<0.001**	**Calamba < Binangonan <Tanay**

Geometric morphometrics

The Principal Component Analysis constructed a rotation of 16 shape variables derived from the set of 10 landmarks used in the study. The Principal Component 1 (PC 1) and Principal Component 2 (PC 2) scores explain 39.63% and 16.61% of the variance, respectively. These PCs do not discriminate among the populations (Figure 3). Three other PCs had variance greater than 5%. Altogether, these first five PCs account for 84.94% of the variance (Table 3).

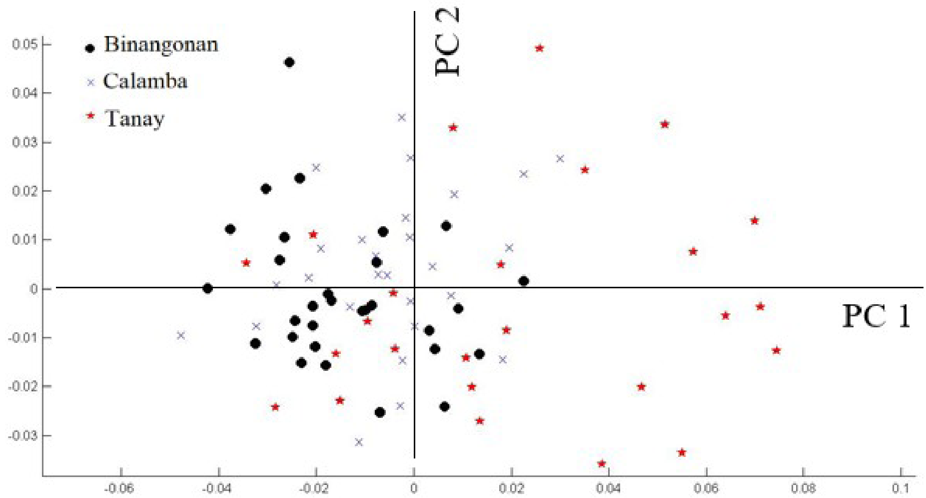

Figure 3. Principal Component Analysis (PCA) plot for 82 specimens of *C. striata* sampled from three areas in Laguna de Bay. PC1 (x-axis) accounts for 39.63% of total variance among individuals and PC2 (y-axis) accounts for 16.61% of total variance among individuals.

Table 3. Eigenvalues and corresponding percentage of variance explained by each Principal Component for specimens of *C. striata*

Principal Component*	1	2	3	4	5
Eigenvalue	0.0007	0.0003	0.0002	0.0002	0.0001
Percent Variation	36.67	16.63	12.25	9.90	6.56

**Only the principal component with percent variance above 5% were shown.*

The results of the MANCOVA performed on the CV 1 and CV 2 scores, as these account for the greatest variation in shape, yielded a significant Wilks λ value of 0.88 (P=0.050). Similarly, to further validate the results of the MANCOVA test, regression of the PC 1 scores against the logarithm of the calculated centroid size for each specimen was done. Regression analysis yielded a non-statistically significant p-value of 0.148 for allometric test, supporting the claim that shape variation was independent of the size of the specimens.

Analysis of shape variation through CVA was done as PCA did not differentiate the three populations clearly. The CVA plot generated in this study showed that Canonical Variate 1 (CV 1) accounts for 70.24% of the total variance, while Canonical Variate 2 (CV 2) accounts for 29.76% of the total variance (Figure 4). CV 1 was able to differentiate the Tanay population from other areas, while CV 2 differentiated the Calamba population from other areas. The shape variation along the x-axis (CV 1) accounted for differences in the posterior aspect of the neurocranium of the specimens, wherein the more positive end is correlated with a longer neurocranium as compared to the more negative end. On the other hand, shape variation along the y-axis (CV 2) correspond to the disparities in the posterior end of the lower jaws of the specimens, wherein the more positive end is correlated with a larger and more elongated head as compared to the more negative end where a more forward lower jaw was observed (Figure 5).

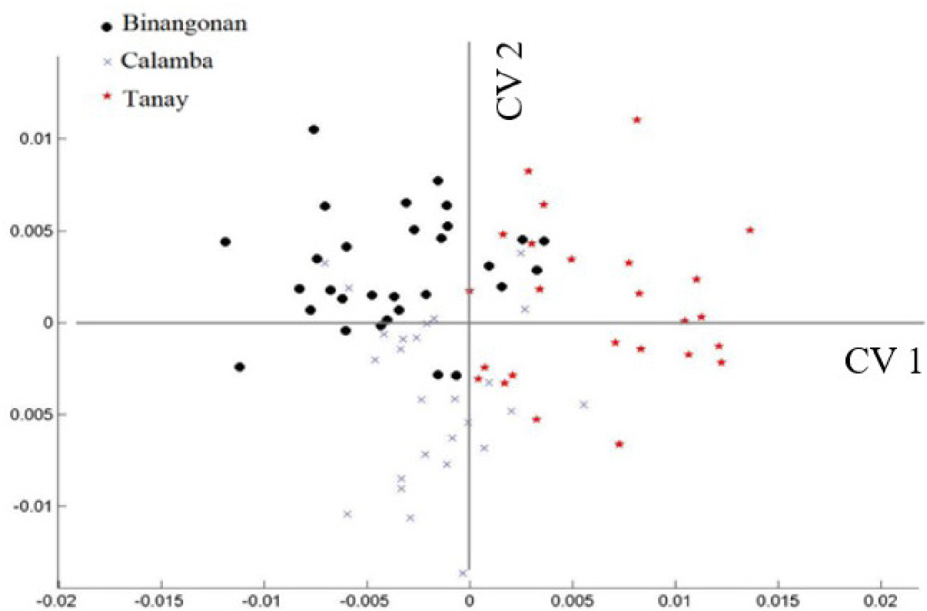

Figure 4. Canonical variate analysis of shape variables of 82 specimens of *C. striata* sampled from three areas in Laguna de Bay. CV1 (x-axis) accounts for 70.24% of total variance among group means and CV2 (y-axis) accounts for 29.76% of total variance among group means.

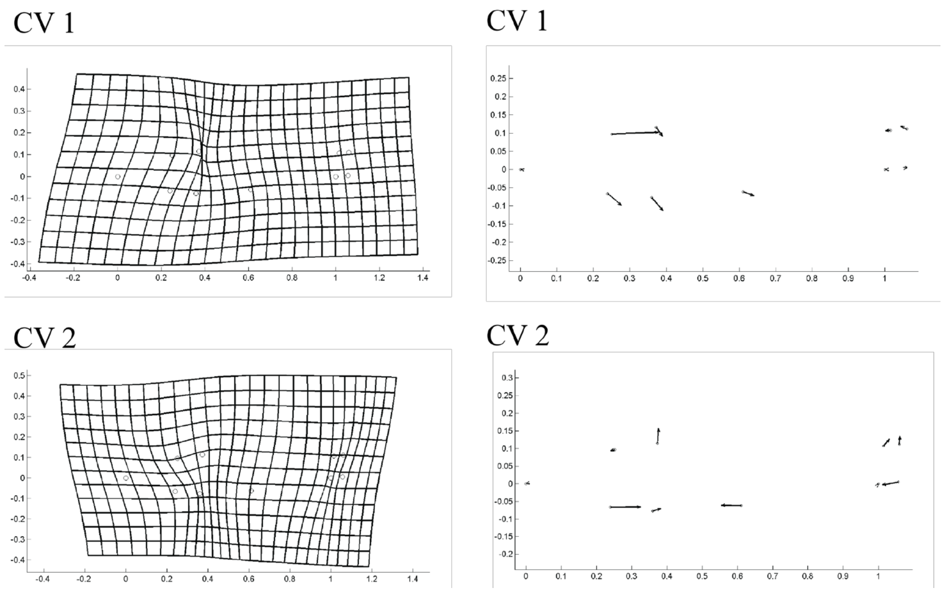

Figure 5. Deformation grids showing the Procrustes deformation and vector diagrams showing the direction and magnitude of shape variations along CV 1 and CV 2 in 82 specimens of *C. striata* across three study sites.

In terms of accuracy of the generated CVA *a posteriori* assignment, correct classification rates of the specimens based on Mahalanobis distances ranged from 70.37% to 80.00% (Table 4). The groupings showed that Binangonan had the lowest percentage of misclassification, wherein only 25.00% (6 out of 24) of the specimens were misclassified under Calamba and Tanay. On the other hand, specimens from Calamba showed the highest percentage of misclassification, wherein 42.10% (8 out of 19) were misclassified under Binangonan and Tanay. Finally, 72.00% of the specimens from Tanay were classified correctly, with 8.00% and 20.00% misclassified as specimens from Binangonan and Calamba, respectively.

Table 4. Canonical variate analysis (CVA) classification for *C. striata*

A priori	*A posteriori*		
	Binangonan	**Calamba**	**Tanay**
Binangonan	24 (80.00%)	2 (6.67%)	4 (13.33%)
Calamba	5 (18.52%)	19 (70.37%)	3 (11.11%)
Tanay	2 (8%)	5 (20.00%)	18 (72%)

Based on the pairwise comparison between populations, shape variation between specimens from each study site was significant (*P*<0.001; Figure 4), with the greatest differentiation observed between Binangonan and Tanay specimens (highest Goodall's F value of 10.64) and least differentiation observed between Binangonan and Calamba specimens (lowest Goodall's F value of 2.78) (Table 5).

Table 5. Pairwise comparisons among sampling areas using Goodall's F-Test and Canonical Variate Analysis-Multivariate Analysis of Variance (CVA-MANOVA). B = Binangonan, C = Calamba, T = Tanay.

Areas compared		N	Goodall's F-Test					CVA-MANOVA			
			F-value	Dist	Df		*P*-value	Wilk's	X	Df	*P*-value
B	T	55	10.64	0.04	16	848.00	<0.001	0.375	44.16	16	<0.001
C	T	52	5.63	0.03	16	0.03	<0.001	0.361	42.75	16	<0.001
B	C	57	2.78	0.01	16	880.00	<0.001	0.493	33.26	16	0.007

Correlation of morphometric values and water quality data

The results of the canonical correlation analysis between the measured morphometric values of the 82 specimens of *C. striata* and physicochemical parameters from Laguna de Bay revealed that the two CVs were statistically significant (Table 6). CV 1 was correlated with total length and pectoral length, while CV 2 was correlated with total weight and total length (Table 8). Specifically, CV 1 correlated total length and pectoral length with total dissolved solid content, while CV 2 correlated total weight and pectoral length with ammonia levels (Table 8). The CCA plot generated revealed an inverse relationship between the morphometric values and physicochemical parameters (Figure 6).

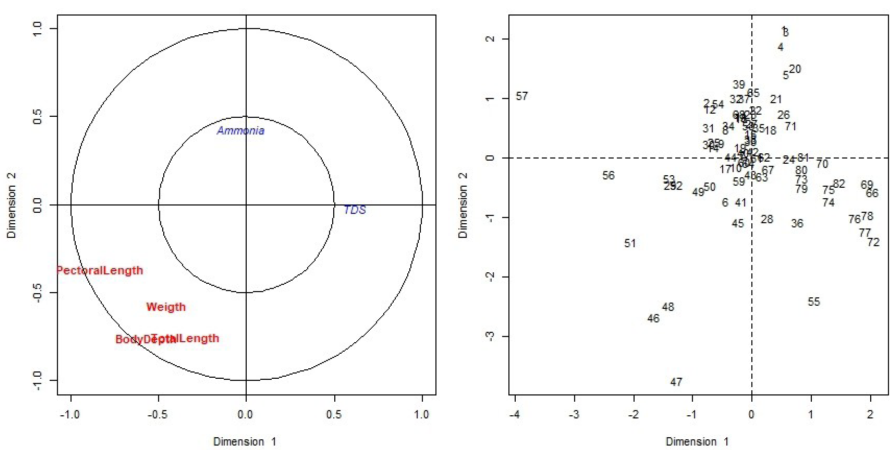

Figure 6. Canonical Correlation Analysis (CCA) plot between measured morphometric values from 82 specimens of *C. striata* and ammonium-nitrogen and TDS content of Laguna de Bay.

Table 6. Canonical correlation analysis between the measured morphometric values from 82 specimens of *C. striata* and physicochemical parameters of Laguna de Bay

Canonical Variate	Canonical Correlation	F-value	p-value
1	0.6140	7.66	<0.001
2	0.4302	5.83	<0.001

Table 7. Canonical correlation analysis between landmark points from 82 specimens of *C. striata* and measured physicochemical parameters of Laguna de Bay

Canonical Variate	Canonical Correlation	F-value	p-value
1	0.7778	2.99	<0.001
2	0.6049	1.85	<0.001

Table 8. Canonical variate loadings showing the correlation between the two CVs (CV 1 and CV 2) and the original variables (morphometric value and physicochemical parameter). Values in bold indicate very high or low CV.

Variables	CV 1	CV 2
Morphometric Variable		
1. Weight	-0.28	1.17
2. Total Length	1.25	**-1.57**
3. Body Depth	-0.38	-0.96
4. Pectoral Length	-1.31	0.67
Physicochemical Parameter		
1. Total Dissolved Solids	1.00	0.05
2. Ammonia	0.05	1.00

Similarly, canonical correlation analysis between the shape variables of the 82 specimens of *C. striata* and the physicochemical parameters from Laguna de Bay revealed that the two CVs were statistically significant (Table 7). CV 1 was correlated with landmark 1 (anterior tip of the snout), landmark 2 (posterior aspect of the neurocranium), landmark 3 (origin of dorsal fin), and landmark 9 (origin of pelvic fin). On the other hand, CV 2 was mostly correlated with landmark 1 (anterior tip of the snout), landmark 2 (posterior aspect of the neurocranium), landmark 3 (origin of dorsal fin), and landmark 10 (posterior end of lower jaw) (Table 9). The CCA plot generated using the shape variables and physicochemical parameters revealed that the cranial region was sensitive to the DO and pH content of the lake (Figure 7).

Table 9. Canonical variate loadings showing the correlation between the two CVs (CV 1 and CV 2) and the original variables (landmark points and physicochemical parameters). Values in bold indicate very high or low CV.

Variables	CV 1	CV 2
Shape Coordinates		
1. Anterior tip of the snout (X)	-2512.09	-1953.39
2. Anterior tip of the snout (Y)	**-27539.89**	**2769.75**
3. Posterior aspect of the neurocranium (X)	-6538.51	**-3083.47**
4. Posterior aspect of the neurocranium (Y)	**-10271.17**	1284.84
5. Origin of dorsal fin (X)	-4512.86	**-2021.76**
6. Origin of dorsal fin (Y)	**-11927.67**	1685.98
7. Insertion of dorsal fin (X)	-1225.03	-681.14
8. Insertion of dorsal fin (Y)	-1469.71	601.33
9. Anterior attachment of dorsal membrane from caudal fin (X)	-1480.41	-817.74
10. Anterior attachment of dorsal membrane from caudal fin (Y)	-1626.45	762.76
11. Posterior end of vertebrae column (X)	-722.23	-977.11
12. Posterior end of vertebrae column (Y)	-1688.77	769.83
13. Insertion of anal fin (X)	-518.49	-715.78
14. Insertion of anal fin (Y)	-1765.35	681.30
15. Origin of anal fin (X)	-450.85	-1420.32
16. Origin of anal fin (Y)	-8755.59	1622.57
17. Origin of pelvic fin (X)	-333.18	-1109.35
18. Origin of pelvic fin (Y)	**-11672.64**	1609.75
19. Posterior end of lower jaw (X)	-849.79	**-1781.21**
20. Posterior end of lower jaw (Y)	-8733.12	1071.93
Physicochemical Parameters		
1. pH	2.00	**-2.96**
2. Dissolved Oxygen (DO)	**-2.75**	2.29

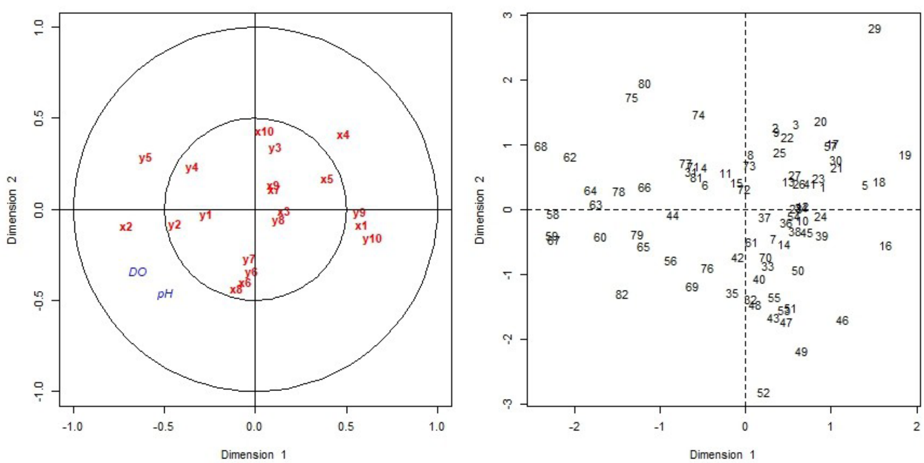

Figure 7. Canonical Correlation Analysis (CCA) plot between landmark points from 82 specimens of *C. striata* and DO and pH content of Laguna de Bay.

DISCUSSION

Channa striata continues to be a top freshwater species, contributing significantly to freshwater fish production in the Philippines. Despite this, detailed information regarding their population remains limited (Jamaluddin et al. 2011). The present study investigated the population of *C. striata* through geometric morphometric analysis. It was revealed that phenotypic variation was present among the populations of *C. striata* within Laguna de Bay. The morphological differences were concentrated on the cranial region, specifically at the posterior aspect of the neurocranium and the posterior end of lower jaw. Similarly, aside from the shape variation observed in the study, differences in the morphometric characteristics of the specimens were also observed. In particular, specimens from the Calamba area had a statistically significant value for total weight, total length, body depth, pectoral length, and centroid size, in contrast with the specimens from Binangonan and Tanay. In terms of the growth pattern, the study yielded a statistically significant Wilks λ value for allometric growth pattern and may indicate that size does not play a notable role in the shape variation of the specimens.

Morphological differences in fishes often account for selection and geographic barriers (Cadrin 2000); however, studies have shown that environmental constraints may also play a part in this process (Su et al. 2018). Variations accounting for environmental differences may reveal insights regarding the ecological strategies of a species, such as feeding habits, movement patterns, and interaction with other species (Santos and Quilang 2012; Yen et al. 2019). The results of the study regarding the higher morphological variation in the cranial region of *C. striata* found in Laguna de Bay were similar to the study done by Yen et al. (2019) for *C. striata* found in Mekong Delta, Malaysia. Yen et al. (2019) explained that usually *C. striata* with a larger head tends to be advantageous, especially when competition for food is present; aggressive behavior in *C. striata* tends to arise when competition is higher, favoring a larger head phenotype.

In terms of the differences in the physicochemical parameters measured among the areas in Laguna de Bay, a statistically significant difference was observed in the ammonium-nitrogen (mg/L) content in the Binangonan area as compared to those in Calamba and Tanay. The observed statistically significant high level of ammonium-nitrogen content in Binangonan might be affected by the rapid land use near the area. Binangonan is mainly surrounded by urbanized and industrialized areas, thus it is possible that waste from these areas, such as organic materials and heavy metals, may have affected the physicochemical parameters near Binangonan (Kosmehl et al. 2008). However, due to the limitations of the study, wherein only secondary data were used, further validation of these results may still be needed.

Canonical variate analysis done on the specimens revealed that the posterior aspect of the neurocranium separated the specimens obtained from the Tanay areas from those obtained from the other areas. Figure 4 shows that the specimens from Tanay clumped together in the positive x-axis, indicating that the specimens from this area have a longer posterior aspect of the neurocranium. On the other hand, Calamba specimens were separated from the other areas through the posterior end of lower jaw, with the specimens clumping together at the negative y-axis. This indicates that the specimens from Calamba had shortened heads and more forward lower jaws compared to the others. Pairwise comparisons among the three populations using Goodall's F-test showed that specimens from Binangonan and Tanay had the greatest variation in shape, and specimens from Binangonan and Calamba had the least variation in shape. The findings indicate that specimens from Binangonan had the largest head region compared to specimens from other areas. These results might help us to better understand the behavior of *C. striata* across the three areas as a response to their environment. The sensitivity of the head region of the *C. striata* to DO content and pH of the lake (Figure 7) may be suggestive of a compensatory mechanism. When the lake has low DO content (hypoxic water), the *C. striata* tends to burrow itself in the mud to keep their skin and breathing apparatus moist (Courtenay and Williams 2004). In this study, although no statistical difference was noted in terms of DO across the areas, still, not so high value of DO with a range of 8.02 to 8.93 mg/L—compared to the 5.00 mg/L minimum standard of the DENR Water Quality Guidelines for Class C waters—was calculated. The longer neurocranium and elongated head of the fish in Tanay may indicate constant use of this part to burrow and breathe in mud.

Likewise, shape variation within the population of *C. striata* in the lake may explain the aquaculture practices found across the three areas. In a study conducted by Santos and Quilang (2012), they noted a higher density of fish pens in the Binangonan area compared to the Calamba and Tanay areas. Fish feeds that diffuse out of the pens may provide nutrients to the nearby waters, giving a greater fitness advantage to fishes near the pens as compared to specimens without, which may translate to a variation in shape. Because of this practice, they found out that *Arius* sp. from Binangonan had the highest correct classification based on the Mahalanobis approach. This result is similar to the results found in this study, where *C. striata* obtained in the Binangonan area had the highest correct classification.

In terms of the morphometric values, length and weight measurements were inversely correlated with high levels of ammonia and total dissolved solids using the CCA. It can be inferred that the elevated ammonia levels in Binangonan may have influenced the morphology of the *C. striata* in the area since it was observed that the average length and weight of *C. striata* were less than the average length and weight of specimens in either Calamba or Tanay. A study by Li et. al in 2014 showed that decreased growth was observed in fish that were exposed to high ammonia levels. Another study by Shin et al. in 2016 showed that elevated ammonia exposure resulted in a decrease in hematological factors, such as red blood cell count, white blood cell count, and hematocrit, as well as in indicators of growth performance such as daily length gain and daily weight gain. The results from these studies mirror the observed pattern in specimens from Binangonan, where a higher ammonia level resulted in decreased growth.

In summary, analysis of the *C. striata* population revealed that variation in morphometric values was observed among specimens across three areas of Laguna de Bay. Among these specimens, *C. striata* from the Binangonan and Tanay areas were the least similar in morphology, with the greatest variation observed in the cranial region. Likewise, specimens from Calamba were found to have the highest morphometric values in terms of length and weight measurements. Assessment of the sampling sites in terms of physicochemical parameters revealed that the ammonium-nitrogen levels in Binangonan was statistically significant compared to the Calamba and Tanay areas. Lastly, the obtained morphometric values were then correlated with the physicochemical parameters of the lake using Canonical Correlation Analysis. CCA reveals that dissolved oxygen and pH content may play a significant role in the cranial region of the fish. On the other hand, weight and length measurements were inversely correlated to high levels of ammonium-nitrate and total dissolved solid content.

For future studies, it is recommended to perform geometric morphometrics in the dorsal head region of the fish to further investigate the variation in head region observed in this study. Likewise, other methods to study the population of *C. striata* is recommended, such as through the use of molecular methods. Genetic analysis may provide a deeper understanding regarding the population structure of this species, as well as the extent of their adaptability to the environment, which can be helpful for management and conservation purposes.

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