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Phenotypic Stock Evaluation of *Plagioscion magdalenae* (Steindachner, 1878): A Species in the Dique Channel in Colombia

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Abstract: Inland fishing is an essential activity for the livelihood and food security the Colombian population. The knowledge and evaluation of exploited fish stocks is a priority to develop sustainable management and conservation strategies of the fisheries. To optimize the management processes of fishery resources and conservation of species, it is necessary to evaluate the population structure and identification of stocks. Geometric morphometrics analysis have shown useful in the evaluation of fish stocks. This study focuses on the species *Plagioscion magdalenae*, commonly called "Pacora", corvinata, or river croaker, which belongs to the family Sciaenidae, a family characterized as an important fishery resource. With the aim of generating a baseline about the state of the *P. magdalenae* population structure, samples were collected along the marshy complex of the Dique channel, Colombia, between December 2020 and October 2021. In this study, the existence of morphometric variability between individuals of *Plagioscion magdalenae* was found across sampling sites, Ciénaga de Capote and Ciénaga del Jobo; shape differences between location suggest the action of environmental pressures and the existence of anthropogenic pressures, such as unsustainable artisanal fishing.

Keywords: pacora; fisheries; stocks; geometric morphometrics; sciaenidae

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1. Introduction

Colombia has great biological and water diversity, being the second richest country in freshwater fish worldwide with approximately 1458 species [1]. From those species, 173 are misused for consumption and only 35 species are not under any degree of threat [2]. Inland fishing is an essential activity for the livelihood and food security of approximately one million people who are part of the communities living in poverty in Colombia [3,4]. Unfortunately, there is evidence of declining catches as a result of the unsustainable use of fish resources and the deterioration of watersheds in the country [2].

According to the fisheries sector and governmental bodies, the proper management of fishery resources is essential for their sustainable use [5,6]. Additionally, due to the considerable increase in fish consumption (9.60 kg per capita in Colombia in 2022) [7], the knowledge and evaluation of exploited fish stocks has become a priority to develop management and conservation plans in the fisheries [8–10]. Despite this, there are no studies that show the current state of exploited populations, especially in artisanal or small-scale fisheries, mainly due to the difficulty in entering the areas where these fishing activities out are carried out and the lack of knowledge or non-compliance with fishing legislation, among others [11]. Likewise, to optimize the management processes of fishery resources and conservation of species, it is necessary to evaluate the population structure and identification of stocks [12–15]. Currently, there are several methods for population determination, such as those based on genetics (mitochondrial DNA, microsatellites, among others) [15], for example, Zheng et al. [16] used mitochondrial DNA to study the variation of genetic diversity and genetic differentiation among populations of the Sciaenidae *Larimichthys polyactis*; likewise, Tesfaye et al. [17] studied genetic diversity in populations of the cichlid *Oreochromis niloticus* in Ethiopia by using nuclear DNA microsatellites.

On the other hand, morphometric differentiation analyses are an important tool in the identification of fish stocks. Morphometric analyses include Truss Network Data, traditional morphometrics, and geometric morphometrics (GM) [18–21]. Geometric morphometry (GM) allows the determination of the morphological variation of specimens and infers a possible population structure of the species [22,23]. It is based on the use of anatomical reference points in coordinates (X, Y) OR (X, Y, Z) in case of 3D analyses, representing the spatial positions of homologous structures in the study organism. GM analyzes the geometric shape resulting from removing the effects of rotation, scale, and translation of organisms after applying a Generalized Procrustes Analysis (GPA) [23–25]. In addition, it provides robust graphical analyses that allow visualization of morphological variation within and between populations [26–28]. The GM has been fundamental for the study of populations, especially in recent decades, where some works, such as Faccenda et al. [20], detail the use of the GM in the identification of stocks of *Oncorhynchus mykiss* (Rainbow trout), finding significant differences in the shape between the three populations studied. Likewise, Ibáñez et al. [29] performed a phenotypic stock discrimination analysis by comparing otoliths of *Mugil curema*, showing that GM allowed them to discriminate by locality (according to otolith shape) to the study samples. Another case study is performed by Pérez-Quiñones et al. [30], where the authors evaluated the hypothesis of the existence of population stock in three localities of *Opisthonema libertate* (Sardine), finding the existence of morphotypes by locality.

This study focuses on the species *Plagioscion magdalenae*, commonly called "Pacora", corvinata, or river croaker, belonging to the family Sciaenidae, a family of fish with commercial and fundamental importance in food safety [31]. It is categorized in the IUCN as DD (Data Deficient), and as VU (Vulnerable) in the Red Book of Freshwater Fishes of Colombia [32,33]. Currently, five species of the genus *Plagioscion* are distributed in South America (Colombia and Brazil) [34]. In Colombia, they are distributed in the Caribbean and in the swamps associated with the Magdalena and Amazon basins that do not exceed 100 m above sea level [2,35]. In the Magdalena River, it is a highly exploited species by the surrounding communities, standing out as an important fishing resource in food sustenance, especially in areas such as the Guájaro reservoir, where the decrease in species typically caught has made the "Pacora" a priority species for fishermen [35,36]. Currently, studies of this species have focused on aspects of reproductive biology [35–37] and on the search for specific sequences microsatellites of Pacora [31]. Even so, there is no information regarding the status of the populations or phenotypic stocks of this important species in the study area.

For this reason, the objective of this study is to quantify the morphological variation through morphometric tools that quantify the geometric shape of *P. magdalenae* in two locations of Zodes Dique, Colombia, and to approximate the state of the phenotypic stock of the species.

2. Materials and Methods

2.1. Study Area

This study was part of a big Colombian grant, which include two sampling locations in Colombia (Ciénagas de Capote UEP1 and Ciénaga de Jobo UEP6), where individuals of *P. magdalenae* were abundant (Figure 1). Both sampling locations are part of the Canal del Dique complex, which is an alluvial plain formed by a complex of wetlands composed of marshes that buffer the flow of the canal, of 113 km in length, from the municipality of Calamar to its mouth in the Bay of Cartagena [3,38].

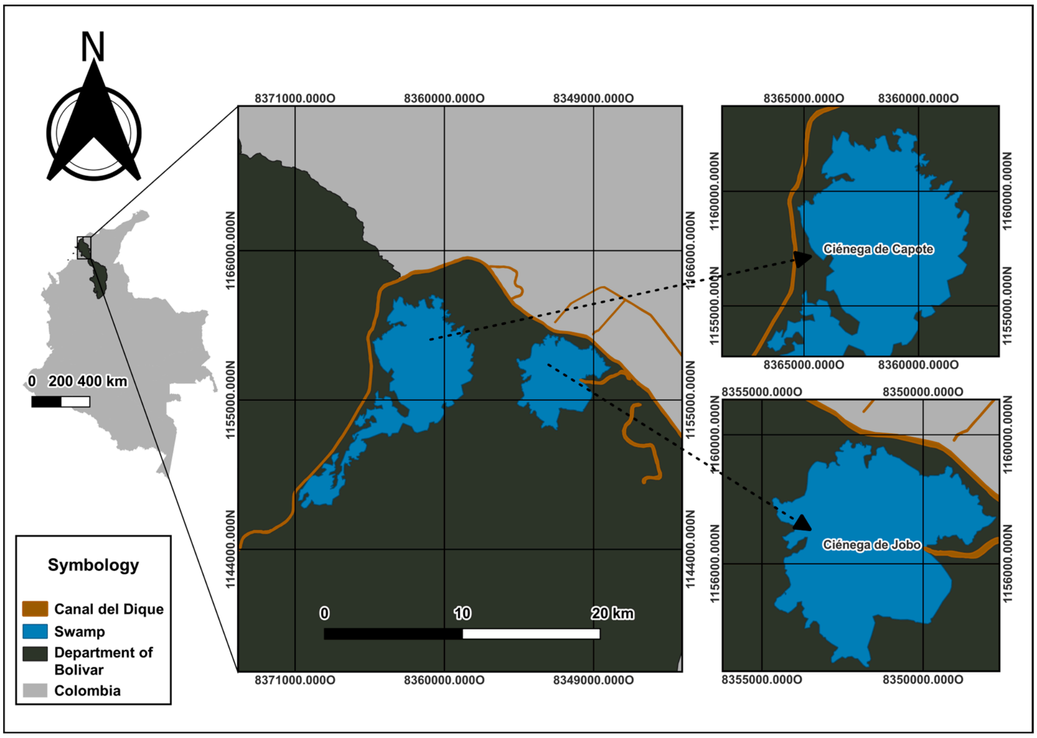

Figure 1. Location of sampling points, UEP1: Ciénaga de Capote (**upper** right), UEP6: Ciénaga del Jobo (**lower** right).

2.2. Field Work and Sample Identification

The samplings were carried out between December 2020 and October 2021. Bimonthly visits of four days each were carried out, in which local artisanal fishermen collected individuals of *P. magdalenae* through artisanal fishing with cast nets and trammel nets throughout the study area. Additionally, GPS data were recorded to the geoposition of the fishing sites at each of the sampling points. The taxonomic identification of the biological material was carried out in situ using the "Colombian Andes Fishes" field guide and the "Colombian Continental Fisheries Resources Catalogue". Subsequently, they were transported in ice cellars to the laboratory where the photographic record was made [2,39]. Eighty-five adult specimens of *P. magdalenae* extracted from the sampling points were analyzed, where sixty-five were UEP6 and twenty were UEP1 (those with mature gonads were taken as adults). The sex was determined by direct observation of the gonads, with fifty females and fifteen males for UEP6, and ten females and ten males for UEP1 [40]. Those with mature gonads were taken as adults. A table with the total length was provided in order to provide a clear representation of sizes of every specimen used in this research (See Supplementary Table S1).

2.3. Geometric Morphometric Analyses

The acquisition of the images was carried out by placing each collected specimen on a white icopor base in an anterior–posterior position with their fins extended by pins. At the time of photography, the scale was defined with the help of a graduated ruler. The photographs were taken with a FUJIFILM X-T2 24 Megapixel high resolution camera. The TpsUtil program was used to transform the photographs to TPS files.

A total of 17 landmarks were established following the criteria of Bookstein [22,41–44], as shown in Figure 2. The morphological landmarks were digitized and transformed to coordinates in a two-dimensional plane using tpsDig2 software [45].

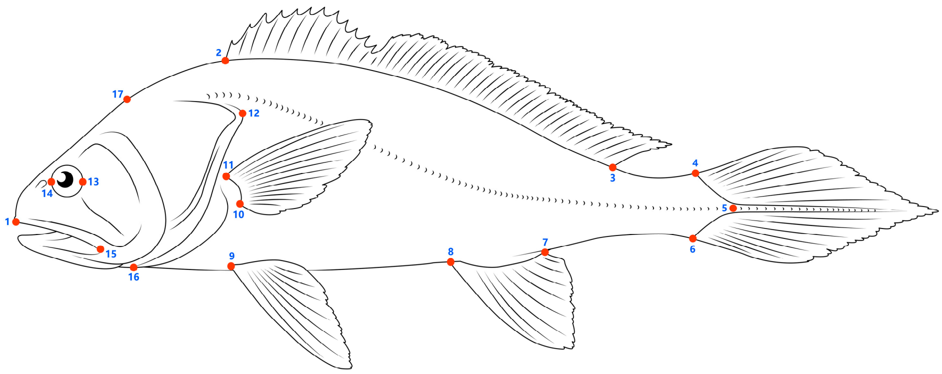

Figure 2. Graphical representation of *P. magdalenae* and landmarks used in this study. 1. Upper tip of the mouth. 2. First spine of the dorsal region. 3. Posterior insertion of dorsal fin. 4. Dorsal base of caudal fin. 5. Ventral insertion of caudal fin. 6. Ventral base of caudal fin. 7. Posterior insertion of anal fin. 8. First spine anal. 9. Anterior base of first pelvic fin ray. 10. Inferior insertion of pectoral fin. 11. Superior insertion of pectoral fin. 12. Dorsal border of preoperculum. 13. Posterior border of eye. 14. Anterior border of eye. 15. Cleft of the upper lip. 16. Anterior margin of the cleithrum. 17. Middle prefrontal region.

Subsequently, the Cartesian coordinates resulting from the placement of landmarks were processed through a Generalized Procrustes Analysis (GPA), based on least squares. This allows averaging the lack of adjustment of all the landmarks, thus detecting the differences between the different configurations. The above is possible because the GPA superimposes the resulting configurations of the analyzed individuals and adjusts them to centroid size one, after eliminating the translation and rotation of the images [25]. Therefore, the GPA allows comparing and describing the shape of the specimens, since it calculates the average configuration that is the summary of all the morphological landmark configurations [23,42,46,47].

Likewise, the measurement error was calculated by digitizing on the same sample the morphological landmarks twice, and using a Procrustes ANOVA, it was compared whether the values of the mean squares (MS) of the individuals were less than the MS of the error [48,49]. Furthermore, a Principal Component Analysis (PCA) was performed to simulate the morphospace of the geometric shapes, generating a scatterplot that plots the first two dimensions of the shape, using the covariance matrix of the shape of the individuals. To graphically observe the changes in shape, the average shapes of the individuals of each locality were obtained, generating a new PCA using the covariance matrix of the average shape, which were superimposed on each other [50,51]. Likewise, in order to visualize how the samples are distributed according to the geometric size (size of the centroid) according to the locality and sex, a violin diagram was made, which allows to represent the comparison of a sample distribution between different categories.

To highlight changes in body shape, a Canonical Variance Analysis (CVA) was performed using a combined sex and locality classifier. It should be noted that this analysis is of the discriminant type, which helps to maximize the variation between groups by creating new shape axes. To determine if there are statistically significant differences in in body shape between location, a permutation test (10,000 permutations) was calculated using Mahalanobis distances (morphological distances extracted after a CVA). All analyses were performed using MorphoJ 1.07d and R using the package geomorph [27,52].

3. Results

Geometric Morphometric Analyses

The measurement error showed that the value of the mean squares of the error was lower than the value of the mean squares of the individuals (MS error: 0.0000026513 < MS individuals: 0.00008383), which means there is no measurement error on the digitized samples (Table 1).

Table 1. Procrustes ANOVA measurement error for *Plagioscion magdalenae* centroid shape size, with SS (Sum of Squares), MS (Mean Square), df degrees of freedom) and F (F-distribution).

Centroid Size:							
Effect	**SS**	**MS**	**df**	**F**	***p* (Param.)**		
Individual	12938.3258	154.027688	84	25.3	<0.0001		
Error 1	517.566663	6.08902					
Shape, Procrustes ANOVA:							
Effect	**SS**	**MS**	**df**	**F**	***p* (Param.)**	**Pillai Tr.**	***p* (Param.)**
Individual	0.21125168	0.00008383	2520	31.62	<0.0001	25.17	<0.0001
Error 1	0.0067608	0.0000026513					

The PCA by locations indicated that the first three PCs explained 72.65% (PC1: 50.96%, PC2: 12.89%, PC3: 11.72) of the variance of the shape of *Plagioscion magdalenae*, showing a differentiation between UEP1 and UEP6 where the specimens of UEP6 used more the morphospace of different shapes (Figure 3).

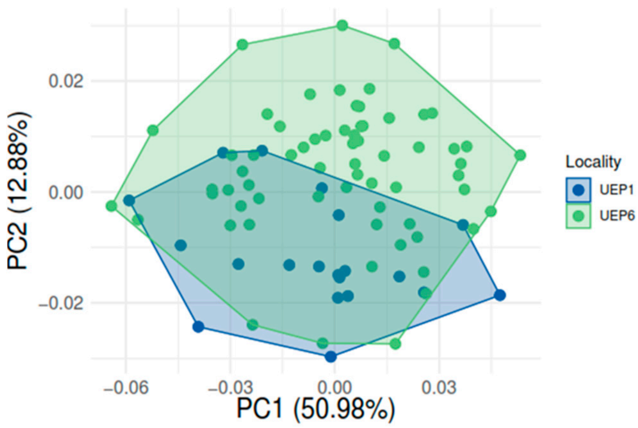

Figure 3. Principal Component Analysis of *Plagioscion magdalenae* between location. The colors represent the different sample locations: blue, UEP1—Ciénaga de Capote, and green, UEP6—Ciénaga de Jobo.

The average PCA (Figure 4) showed disparities in shape between locations. UEP6 individuals were observed to have a slightly more elongated body shape compared to UEP1 individuals. Significant movement were evident at anatomical landmarks 10, 12, and 13, corresponding to pectoral fin ventral insertion, dorsal insertion of the upper pectoral, and posterior edge of the operculum, respectively. Small upward displacements of landmarks 16, 9, and 8 were also observed in UEP6 corresponding to the anterior margin of the cleithrum, the ventral fin insertion, and the first anal column, which seems to indicate that UEP1 individuals exhibit a larger ventral area.

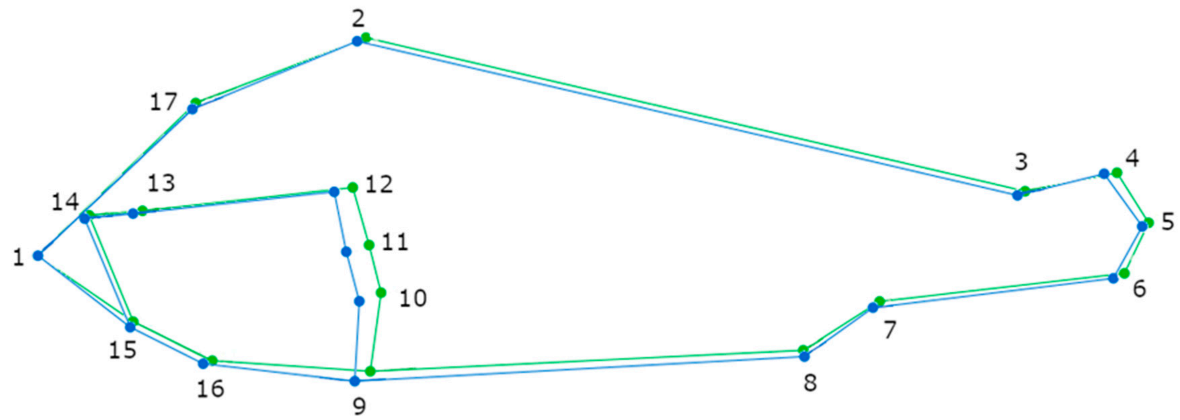

Figure 4. Wireframe of the average shape between the specimens of UEP1 and UEP6, Table 1. Blue, UEP1—Ciénaga de Capote, and green, UEP6—Ciénaga del Jobo.

On the other hand, the violin diagram showed that UEP1 individuals tend to be larger in size than those of UEP6. It is also evident that females have a greater size dispersion than males (Figure 5).

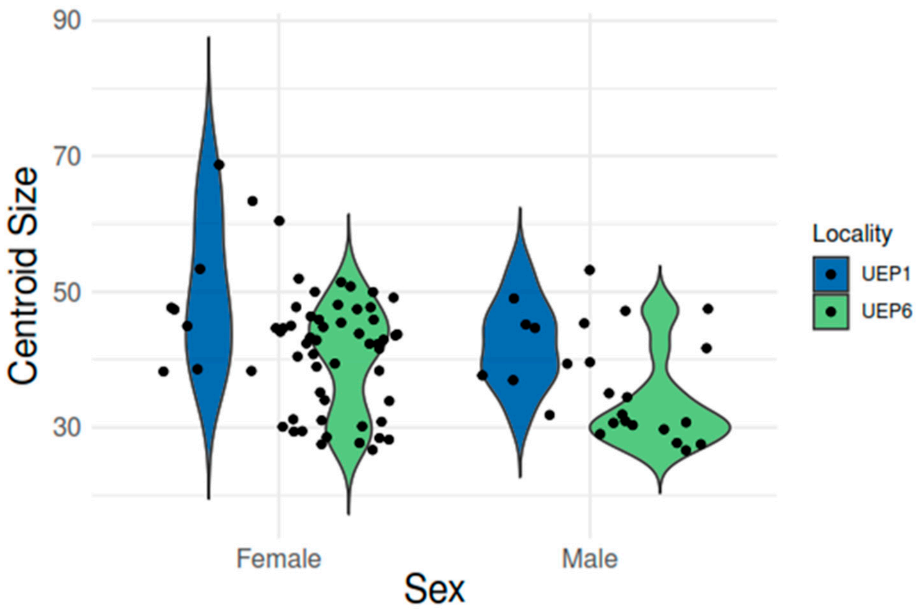

Figure 5. Violin diagram of the centroid size of *P. magdalenae* between location. Blue, UEP1—Ciénaga de Capote, and Green, UEP6—Ciénaga del Jobo.

The Canonical Variate Analysis (Figure 6) confirmed the presence of morphological disparity in the body shape of *P. magdalenae* with a clear difference between locations.

In addition, sexual shape dimorphism was visualized among the individuals of UEP1, these disparities were also significant after performing the permutation test using the Mahalanobis distances (Table 2).

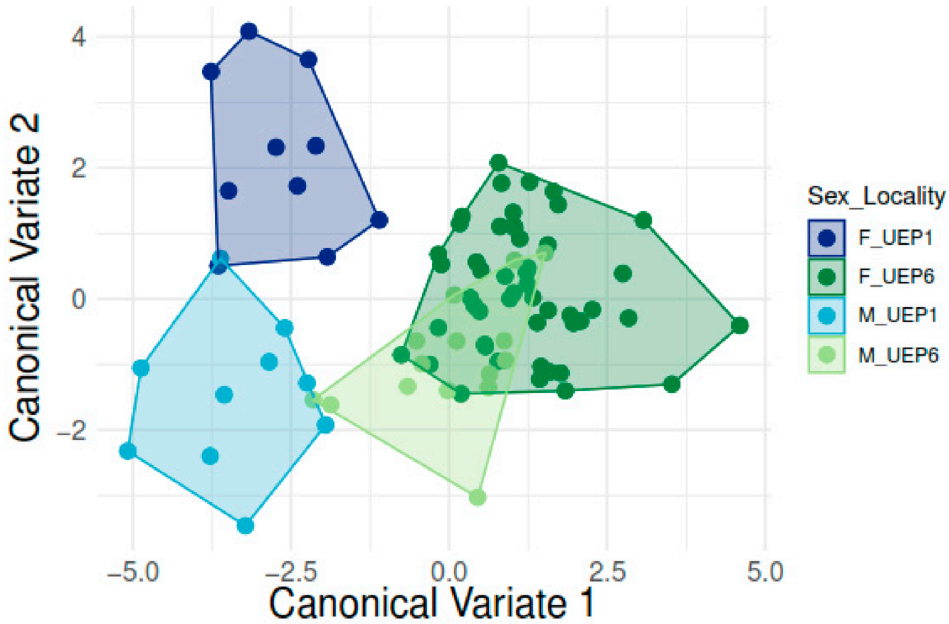

Figure 6. Canonical Variate Analysis using the classifier sex and locality. Colors represent the different population and their respective sex. Light blue: males of UEP1, light green: males of UEP6, dark blue: females of UEP1, and dark green: females of UEP6.

Table 2. Permutation test based on Mahalanobis distances between populations and sexes of *Plagioscion magdalenae*, with female Ciénaga de capote (H/UEP1) and Ciénaga de Jobo (H/UEP6), and male Ciénaga de capote (M/UEP1) and Ciénaga de Jobo (M/UEP6).

	H/UEP1	**H/UEP6**	**M/UEP1**
H/UEP6	4.4373		
p-value	<0.0001		
M/UEP1	3.997	4.8907	
p-value	<0.0001	<0.0001	
M/UEP6	4.2608	2.5741	4.3786
p-value	<0.0001	<0.0001	<0.0001

4. Discussion

The results of this study show the existence of morphological differences between individuals of *Plagioscion magdalenae* from different locations sampled, Ciénaga de Capote and Ciénaga del Jobo. The body shape of the individuals of UEP6 is slightly more elongated, and motion is denoted towards the caudal area of the operculum region, compared to the individuals of UEP1 that are slightly more compact antero-posteriorly. These morphological differences between the locations can suggest the action of environmental pressures, which agrees with what was previously reported by Hernandez et al. [53], where it was found that the body shape of the cichlid *Caquetaia kraussii* was influenced by environmental pressures and varied according to the environment where it developed. The researchers showed that *C. kraussi* adopted an elongated shape and different hydrodynamics when they developed in lotic environments (when there is flow or movement of water), on the contrary, when the growth is in lentic environments (when there is flow or movement of water), it showed a more compact and robust body shape. This behavior of morphometric variation subject to the environment where the species develop is also supported by Gaston and Lauer, [54], evidencing the presence of morphometric variation of individuals of *Lepomis macrochirus* and *Lepomis cyanellus*, founding that the body shape of the individuals changes according to the habitat, i.e., whether it is lentic or lotic. Additionally, it has been previously highlighted that individuals from lentic environments have a deeper and more compressed body shape, which influences better maneuverability when swimming [55]. It was also observed that

UEP1 individuals are larger than UEP6 organisms; this could indicate the presence of anthropogenic pressures [56] acting differently at each of the locations (Ciénaga de Capote and Ciénaga del Jobo), including activities such as fishing, unsustainable craft, the use of unauthorized fishing gear, violation of current regulations, overfishing by fishermen, which are situations that occur daily in this swampy complex of Canal del Dique [57]. This agrees with Narváez Barandica at al. [58], who found that fishing gear was responsible of overexploitation of four out of five commercially important species in the Ciénaga Grande de Santamarta, Colombia. The existing impact of fishing gear on the fish indicated by Narvaes in his study, is reinforced by what was evidenced by Liang et al. [59], where they indicate that the environment and fishing gear generate changes in the growth traits of commercially exploited species, influencing smaller size for age and smaller maturation sizes, among other affectations. In the case of *Plagioscion magdalenae*, a decrease in the mean size at maturity (L50) and body size has been observed in recent years. In this work, the mean size at maturity was carried out according to the criteria of Cubillos et al. [60] and Paramo and Nuñez [61]. A supporting logistic model and maximum likelihood based on Least Squares obtained L50 data that was 29.69 cm of Total Length (TL) for Ciénaga del Jobo and 32.9 cm (TL) for Ciénaga de Capote (Bermudez pers com). In addition, mature individuals between 20–30 cm in TL were observed, which is well below the average mature size defined for the species. This observation could indicate that the species is adapting in response to fishing pressures (artisanal fishing, fishing gear without the permitted requirements) present in both swamps by maturing to earlier sizes. In the same way, the catalog of continental fishing resources of Colombia [2] for the year 2006 indicates that the average size at maturity of *P. magdalenae* was 38.7 cm SL, which is well above the minimum size of capture of 30 cm for 2007; it was discriminated between males and females, obtaining a L50 of 39 cm for females and 29 cm for males, and for 2008, the (L50) was 37 cm SL. On the other hand, Barbosa-Santos et al. [36] showed L50 below 30 cm considering both sexes, with a L50 of 31 cm for males and 28 cm for females. Likewise, a similar result was observed by Rojas-Luna and García-Alzate [35], finding that the L50 was below the mean catch size (30 cm). Thus, fishing gear presents different types of selection on fish, affecting mainly the body length, but can also affect the body size of the fish. The latter is reinforced by what was published by Mangi and Roberts [62], when quantifying the environmental impact of artisanal fishing in coral reef ecosystems, finding that 150 of 195 species captured with the different fishing gears had size maturation and length well below the average, which would be indicating overfishing of juveniles. On the other hand, it is important to highlight that the presence of anthropogenic pressures, such as artisanal fishing, can affect the size and sex of the organisms, thus affecting reproduction. This is supported by Lloret et al. [63], where their study on the threats of artisanal fishing to the reproduction of coastal fish species showed that it not only affects the reproduction of fish species, but it can also exacerbate the impact of fishing on coastal resources instead of reducing them.

Adding to the above, the CVA showed the presence of sexual dimorphism size; it was evidenced that females are generally larger than males. Rojas-Luna and García-Alzate [35] indicate that this behavior is due to the fact that *P. magdalenae* females have a high energy demand due to physiological and reproductive processes (spawning migration, yolk accumulation in the maturation phase of gonads, among others) [64]. Along the same lines, it seems that DTS influences females more than males, precisely because of reproductive aspects, as indicated by López-Cepeda et al. [65], whose study analyzed the morphometric differences in *Poeciliidae Gambusia holbrooki*, finding significant differences in the size of females and males, determining that females are larger than males [66].

The morphometric variations and the anthropogenic pressures detected in this study provide an initial important approach for the evaluation of the phenotypic stock in *Plagioscion magdalenae* in these two study locations. Likewise, it demonstrates how important population evaluation studies are for species such as *P. magdalenae*, which are commercially important and are part of the food security of the fishing communities surrounding the study area [67,68]. It is also imperative to complement what is provided here for the species with population genetic studies and/or studies that help to have a better understanding of the impact of artisanal fishing as anthropogenic pressure on *P. magdalenae*. These investigative efforts become essential when developing and implementing actions [69,70] for sustainable management and elaboration of conservation plans that encourage sustainable management for this species with aquaculture potential in the Dique Channel in Colombia, to provide a lasting resource to Colombian communities.

5. Conclusions

The following research represents the first approach to evaluate the phenotypic stock of *Plagioscion magdalenae* related to the consequences of artisanal fishing. Morphological variations were found to influence the entire shape of *P. magdalenae* between the sample locations. An important shape influence was found in UEP1—Ciénaga de Capote, which was morphologically expressed with a response to have smaller body sizes compared to individuals from UEP6—Ciénaga del Jobo, suggesting fishing pressure on individuals from UEP1, affecting size and shape.

The presence of sexual size dimorphism may show an influence in the reproductive traits of *P. magdalenae*. As a consequence, the energy demand that the females require to carry out their physiological and reproductive processes was found to generate a more robust shape in females.

This work highlights the advantages of Geometric Morphometrics (GM) as a low-cost tool in the analysis of phenotypic stocks. The precision of GM to detect shape patterns of variation in the body of the studied species has allowed us to reveal and graphically represent the morphometric differences different multiple different populations. Nevertheless, a combination of complex tools for population genomics is recommended for future studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes8040173/s1.

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Institutional Review Board Statement: The Ethics review board of the University of Cartagena considers that this type of project does not fall under the legislation for the protection of animals used for scientific purposes, national decree-law 113/2013 (2010-63-EU directive). It considers that this type of project has no impact on animal welfare because all procedures are carried out after the animal has been sacrificed, and the legislation for slaughter in certified slaughterhouses is respected. The animals used for the Manuscript "Phenotypic stock evaluation of *Plagioscion magdalenae* (Steindachner, 1878) a species with aquaculture potential in the Dique channel in Colombia" were slaughtered at a commercial abattoir in accordance with the Council Regulation, EC, No. 1099 (2009) concerning the protection of animals at slaughter.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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

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