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Climate Change Impact on Morphological Adaptation of the West African Croaker (*Pseudotolithus elongatus*) in the Cross River Estuary, Nigeria

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ABSTRACT

Climate change significantly affects aquatic ecosystems, driving morphological and physiological adaptations in estuarine fish. This study examined the impact of salinity, temperature, and dissolved oxygen variations on the morphological traits of *Pseudotolithus elongatus* in the Cross River Estuary, Nigeria. Over a 12-month period, a total of 240 fish samples were collected across three salinity zones (low: <10ppt, medium: 10–20ppt, high: >20ppt). Key environmental parameters were recorded alongside morphological measurements, including body depth, caudal fin length, and total length. Data analysis involved ANOVA, Pearson correlation, principal component analysis (PCA), and multiple linear regression. Significant morphological differences were observed among salinity zones, with deeper bodies and larger caudal fins in higher salinity zones, reflecting adaptations to stronger tidal currents and elevated salinity. Temperature positively correlated with body depth ($R^2 = 0.87$, $P < 0.001$), highlighting thermal stress as a driver of morphological shifts. The analysis of the principal components identified body depth and caudal fin length as the main contributors to morphological variation, explaining 47.2% of the variance. Regression analysis revealed salinity and temperature as significant predictors of body depth (Adjusted $R^2 = 0.72$, $P < 0.001$), while dissolved oxygen showed a modest negative effect. These findings underline the plasticity of *P. elongatus* in response to climate-induced environmental changes, with implications for fisheries management under shifting ecological conditions. Adaptive strategies incorporating environmental monitoring and sustainable resource management are recommended to mitigate climate change impacts on fish populations.

INTRODUCTION

Climate change is an undeniable driver of environmental shifts, leading to profound transformations across ecosystems globally. One of the most impacted environments is the estuary, which serves as a delicate interface between freshwater and marine ecosystems **(Shivanna, 2022)**. Estuaries are inherently dynamic, with fluctuating conditions of salinity, temperature, and hydrodynamics, making them particularly vulnerable to the effects of climate change. These changes often manifest as increased temperature extremes, altered rainfall patterns, and rising sea levels, all of which exacerbate environmental stress in aquatic environments. As climate change continues to influence estuarine ecosystems, the species inhabiting these areas, particularly estuarine fish, face an array of challenges in adapting to rapidly shifting conditions **(Nwosu *et al*., 2016)**.

The West African croaker, *Pseudotolithus elongatus* (with other croaker species), is a commercially valuable estuarine fish species that plays a significant role in the artisanal fisheries of West Africa. This species is particularly important in Nigeria, where it contributes to local food security and the livelihoods of communities who rely on fishing as their primary economic activity **(Holzlohner *et al.*, 1998; Holzlohner *et al.*, 2004; Asuquo & Ifon, 2021; Otogo *et al.*, 2022)**. Fish are highly valued in both domestic markets and international trade, making it a key resource for regional economies. The Cross River Estuary in southeastern Nigeria provides a critical habitat for *P. elongatus*, supporting local fisheries that supply fresh fish to markets across the region **(Asuquo & Ifon, 2019; Otogo, *et al*., 2023)**. However, with the ongoing impacts of climate change, including rising temperatures, altered rainfall patterns, and increased salinity gradients, the habitat of this fish is being altered. These changes can directly affect the survival, productivity, and morphological traits of fish populations, including *P. elongatus*, which in turn can have profound economic consequences for the local communities dependent on this species **(Asuquo & Ifon, 2022a)**.

As global warming and changes in precipitation patterns intensify, the environmental conditions of the Cross River Estuary are shifting. The region is experiencing rising temperatures, altered rainfall distribution, and increased salinity gradients, which have the potential to disrupt the delicate balance of the ecosystem. These environmental stressors can significantly affect the physiological processes and biological characteristics of species that rely on estuarine habitats for breeding, feeding, and growth **(Ifon & Asuquo, 2021)**.

The adaptability of *P. elongatus* to these shifting environmental conditions is of particular interest, especially in terms of its morphological adaptations. Morphological traits such as body shape and length, pigmentation, scale growth in radius and circuli, fin structure, and body depth can be influenced by environmental factors like salinity and temperature **(Asuquo & Ifon, 2022b)**. Phenotypic plasticity, the ability of an organism to modify its morphology in response to environmental changes, allows fish to enhance their survival in varying conditions. For example, in regions of high salinity, fish may evolve deeper bodies that provide greater stability, while in areas with stronger water currents, more elongated fins may provide better propulsion. These adaptations play a critical role in enhancing the fish's swimming efficiency, foraging success, and resilience to predation. Understanding the mechanisms underlying these changes is crucial for assessing the species' ability to cope with the challenges posed by climate change.

Research on the morphological adaptations of estuarine fish to climate change is limited, particularly in tropical ecosystems where the impact of climate change is expected to be more pronounced due to their sensitivity to fluctuations in environmental parameters **(Kipanyula & Maina, 2016)**. While studies in temperate regions have documented how climate-induced stressors affect the growth, reproduction, and morphology of marine organisms, there is a noticeable gap in the literature regarding tropical estuarine species like *P. elongatus*. This lack of data makes it difficult to predict how such species will respond to ongoing environmental changes, particularly in regions where estuarine fisheries are of economic and ecological importance.

The Cross River Estuary offers a unique opportunity to investigate the effects of climate change on the morphology of *Pseudotolithus elongatus* in a tropical estuarine environment. The study focuses on understanding how the species adapts to variations in salinity and temperature, two key environmental factors that are influenced by climate change. By examining these morphological changes, the study aimed to provide insight into the adaptive capacity of the species, highlighting the role of phenotypic plasticity in allowing estuarine fish to cope with environmental stress. This knowledge is crucial not only for understanding the species' resilience to climate change but also for informing conservation and fisheries management strategies in the face of rapidly changing climatic conditions.

Recent studies have begun to explore how salinity and temperature influence fish morphology, but few have linked these changes directly to climate variables in tropical estuarine ecosystems **(Hossain *et al*., 2016; Asuquo & Ifon, 2019; Bonamour *et al*., 2019)**. This study seeked to fill this gap by investigating the relationship between these key environmental factors and the morphological traits of *P. elongatus*, using the Cross River Estuary as a case study. Through this approach, the research aimed to contribute valuable data to the understanding of how tropical estuarine species can adapt to the ongoing pressures of climate change.

By integrating morphological assessments with environmental data, the study offers a comprehensive analysis of the adaptive strategies employed by *P. elongatus* in response to climate-induced stress. This knowledge is critical for informing sustainable fisheries management practices, ensuring the resilience of local fish populations, and supporting the livelihoods that depend on them. Ultimately, this research contributes to the broader understanding of biodiversity resilience in tropical ecosystems, offering insights that are applicable to other estuarine species facing similar environmental challenges.

MATERIALS AND METHODS

Study area

The study was conducted in the Cross River Estuary, located in southeastern Nigeria, at geographical coordinates approximately 4°30' N latitude and 8°20' E longitude (Fig. 1). This estuarine system lies between the town of Calabar and the boundary with the Republic of Cameroon to the east. The Cross River Estuary covers a significant portion of the coastal zone, extending from the river mouth near the Atlantic Ocean inland to the freshwater inflows from the Cross River. It is bordered by the Atlantic Ocean to the south, and its upper reaches are influenced by the surrounding wetland and forested areas of southeastern Nigeria **(Eteng & Ifon, 2019)**.

The estuary is characterized by a complex network of habitats, including mangrove swamps, tidal creeks, mudflats, and freshwater influxes. These habitats are crucial for a variety of marine species and support local fishing communities. The salinity and temperature of the estuary vary considerably across the region due to the interplay of tidal fluctuations, seasonal rainfall, and freshwater input from the Cross River **(Ameh *et al.*, 2023)**. The salinity gradient is shaped by the interaction between freshwater from the river and the saline waters from the ocean, which vary depending on the tidal cycle and the time of year.

The climate of the region is tropical, with distinct wet and dry seasons. The wet season typically lasts from April to October, characterized by heavy rainfall, which significantly dilutes the salinity of the estuary, particularly in the upper reaches **(Otogo *et al.*, 2023)**. The dry season, from November to March, is marked by reduced rainfall, higher evaporation rates, and an increase in salinity as seawater influence becomes more dominant. Average annual temperatures in the estuary range from 26 to 30°C, with higher temperatures observed during the dry season, particularly between December and February. These climatic factors—seasonal temperature variations, rainfall patterns, and tidal influences—create a dynamic environment in which the morphological characteristics of estuarine species, such as *Pseudotolithus elongatus*, may adapt to the changing conditions.

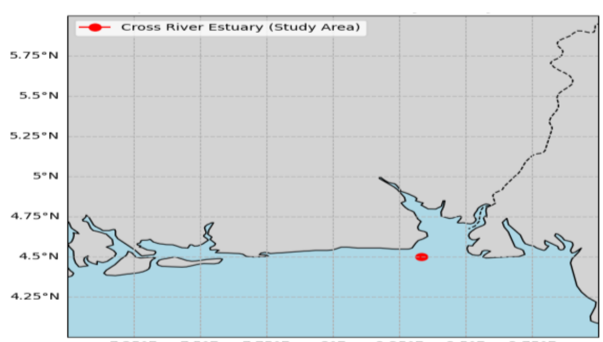

Fig. 1. Map of the Cross River Estuary (Study area)

Sampling strategy

Fish were sampled monthly across the three salinity zones. A total of 240 adult specimens of *Pseudotolithus elongatus* were collected using gill nets (mesh size: 3–5cm) and cast nets during high and low tides. Specifically, 80 specimens were obtained from each salinity zone. The average weights of the fish collected were 385.2 ± 24.5g in the low-salinity zone, 412.7 ± 28.1g in the medium-salinity zone, and 439.3 ± 22.9g in the high-salinity zone. Environmental parameters, including salinity and water temperature, were measured *in situ* using a YSI multiparameter probe (Model 556 MPS). Salinity was recorded in parts per thousand (ppt), and temperature was recorded in degrees Celsius (°C).

Morphological measurements

The morphological traits of each fish were carefully measured using digital calipers with a precision of 0.01cm to ensure high accuracy. The key traits measured included total length, body depth, and caudal fin length. Total length (TL) was defined as the distance from the tip of the snout to the end of the caudal fin. Body depth (BD) was measured as the maximum vertical height of the fish's body, and caudal fin length (CFL) was taken as the length from the base to the tip of the caudal fin.

To ensure measurement reliability, each trait was measured three times, and the average of these measurements was recorded. Additionally, each fish was photographed alongside a scale bar to visually verify the accuracy of the measurements during the data analysis stage. This photographic documentation helped maintain consistency and ensured the integrity of the morphological data collected.

Experimental design

The study utilized a completely randomized design (CRD) with three salinity zones: low (<10ppt), medium (10–20ppt), and high (>20ppt) as treatments. These zones were defined based on measured salinity levels in different locations within the estuary, reflecting the varying influence of freshwater and seawater at different times of the year. The low salinity zone is influenced predominantly by freshwater inflows, while the high salinity zone is located closer to the estuarine mouth, where seawater dominates. The medium salinity zone lies between these two extremes, representing a mix of both freshwater and marine influences. This stratification enabled an investigation of how *Pseudotolithus elongatus* responds morphologically to varying environmental conditions within the estuary. Morphological traits were treated as the dependent variables, while salinity and temperature served as the independent variables.

Fish and water sampling

Water samples were collected using a clean, sterile plastic bucket (or an appropriate container) to avoid contamination and preserve the integrity of the water sample. For salinity and temperature measurements, a digital salinometer (model: YSI ProDSS) and a hydro thermometer (model: Omega Engineering HH21) were used to determine the *in situ* salinity and temperature in each sampling location. These instruments were chosen for their high accuracy and ability to provide real-time, reliable measurements of the water's temperature and salinity, without the need for water sample preservation, making them ideal for field conditions.

In situ measurement of salinity and temperature is essential in this study, as it ensures that the data reflect the actual environmental conditions at the time of sampling. Given the variability of these parameters in estuarine ecosystems due to tidal fluctuations, seasonal changes, and local factors, measuring them directly in the field minimizes the risk of alterations that may occur during transportation and storage of water samples. Additionally, *in situ* measurements allow for real-time data collection, which is critical for understanding the dynamic, rapidly changing nature of estuarine environments, especially in the face of climate change. By using these instruments in the field, we were able to obtain accurate and up-to-date environmental data, crucial for correlating with the morphological traits of *P. elongatus*.

Fish samples were collected concurrently in the three designated salinity zones (low, medium, and high) from multiple locations within each zone. Fish were captured using a combination of gill nets, cast nets, and hook-and-line methods to ensure a representative sample of juvenile and adult fish across a range of sizes.

Statistical analysis

The data were analyzed using several statistical methods to assess the relationships between morphological traits and environmental variables. Descriptive statistics were first computed, including the mean and standard deviation for each morphological trait, to provide an overview of the data distribution. To determine if there were significant differences in morphological traits across the different salinity zones, one-way Analysis of Variance (ANOVA) was performed. A post-hoc Tukey test was subsequently conducted to pinpoint specific differences between the salinity zones.

To further investigate the relationships between morphological traits and environmental variables such as temperature and salinity, Pearson correlation coefficients were calculated. This analysis allowed for the identification of significant correlations and their strength. Additionally, Principal Component Analysis (PCA) was employed to examine the primary morphological traits contributing to the variation across the salinity zones. The first two principal components (PC1 and PC2) were visualized in a biplot, which provided insights into how the morphological traits clustered in relation to the salinity zones.

Finally, linear regression models were applied to analyze the effect of temperature on body depth. The strength of the relationship was quantified using R^2 values, which indicated the proportion of variation explained by temperature. All statistical analyses were conducted using R (Version 4.3.1), and visualizations were generated with the ggplot2 package. A significance level of 0.05 was used for all tests to determine statistical significance.

Ethical considerations

The study followed ethical guidelines for the use of aquatic organisms in research. Fish were handled humanely, minimizing stress during sampling and measurement. All experiments were approved by the Institutional Animal Care and Use Committee (IACUC) of the University of Calabar, Nigeria.

Quality control

To ensure the reliability and accuracy of the data collected, several quality control measures were implemented throughout the study. Prior to use, all instruments, including the digital salinometer and hydro thermometer, were calibrated according to the manufacturer's instructions to ensure accurate readings. For morphological measurements, each fish was measured three times, and the average value was recorded to minimize measurement errors. Additionally, to further validate the results, random samples of both fish and water measurements were cross-checked by an independent observer. This process was implemented to reduce potential biases and to ensure that the data collected were consistent and reliable across all sampling periods. These quality control procedures helped maintain high standards of data integrity and ensure the robustness of the study’s findings.

RESULTS

Salinity, temperature, and dissolved oxygen variations across climate gradients

Salinity, temperature, and dissolved oxygen levels are crucial environmental variables influencing the habitat and biology of estuarine fish. Across the study area in the Cross River Estuary, significant variations were observed in these parameters across the three salinity zones (low, medium, and high) over the 12-month sampling period. Salinity levels showed a clear spatial variation, with the low salinity zone (<10ppt) exhibiting average values ranging from 1.5ppt in the rainy season to 8.7ppt during the dry season. The medium salinity zone (10–20ppt) had values between 8.1 and 17.3ppt, and the high salinity zone (>20ppt) ranged from 21.4 to 30.6ppt, peaking during the dry season when freshwater influx was reduced (Table 1). These seasonal fluctuations in salinity were closely linked to changes in river discharge, rainfall patterns, and evaporation rates.

Temperature variation across the estuary also displayed significant seasonal changes. The average temperature in the low salinity zone was 28.3°C in the rainy season and increased to 31.0°C during the dry season. In the medium salinity zone, temperatures ranged from 27.8 to 30.5°C, and in the high salinity zone, temperatures fluctuated from 28.4 to 30.8°C. The elevated temperatures during the dry season likely contributed to thermal stress, particularly in the high salinity zone, where temperature and salinity co-vary. Dissolved oxygen levels varied inversely with salinity. In the low salinity zone, DO concentrations were consistently higher, ranging from 4.9 to 6.5mg/ L, due to higher freshwater input. However, in the high salinity zone, DO levels fluctuated between 3.2 and 5.0mg/ L, with lower values observed during the dry season when tidal influence was stronger and water exchange less efficient. These variations in oxygen levels can be critical for fish respiration and overall health.

The results demonstrate that salinity, temperature, and dissolved oxygen levels follow distinct seasonal patterns, influenced by both climatic conditions and tidal variations. These fluctuations create a dynamic environment for *P. elongatus*, with each salinity zone presenting unique challenges and selective pressures on the fish's survival and morphological development.

Table 1. Variation in environmental parameters (Salinity, temperature, and dissolved oxygen) across salinity zones

Salinity zone	**Salinity (ppt)**	**Temperature (°C)**	**Dissolved oxygen (mg/L)**
Low (<10ppt)	1.5–8.7	28.3 (rainy) – 31.0 (dry)	4.9 – 6.5
Medium (10–20ppt)	8.1–17.3	27.8 (rainy) – 30.5 (dry)	3.8 – 5.2
High (>20ppt)	21.4–30.6	28.4 (rainy) – 30.8 (dry)	3.2 – 5.0

Morphological variation across climate gradients

The morphological traits of *Pseudotolithus elongatus* exhibited significant variation across the different salinity zones, closely correlating with the environmental gradients observed in the study. Fish from the high-salinity zone had deeper bodies (10.1 ± 1.4cm) and larger caudal fins (5.5 ± 0.8cm) compared to their counterparts in the low-salinity zone, which had shallower bodies (8.5 ± 1.2cm) and smaller caudal fins (4.8 ± 0.6cm). The total length of fish also varied significantly, with individuals from the high-salinity zone averaging 36.2 ± 2.7cm, compared to 32.5 ± 2.8cm in the low-salinity zone (Table 2).

These morphological differences suggest adaptations to the distinct hydrodynamic and salinity conditions in each zone. For instance, the deeper bodies observed in the high-salinity zone likely provide increased stability in areas with stronger tidal currents and higher salinity, while the larger caudal fins enhance propulsion efficiency. In contrast, the more streamlined body shapes and smaller caudal fins in the low-salinity zone may reflect adaptations to less turbulent conditions, prioritizing energy efficiency in calmer waters. Fish from the medium-salinity zone exhibited intermediate morphological traits, with body depths of 9.3 ± 1.5cm, caudal fin lengths of 5.1 ± 0.7cm, and total lengths of 34.8 ± 3.1cm, highlighting a transitional adaptation between the low and high salinity zones.

These findings underscore the role of environmental variables such as salinity and temperature in driving morphological plasticity in *P. elongatus*. Adaptations in body depth, caudal fin length, and overall size likely optimize swimming efficiency, foraging success, and survival across these climate-induced environmental gradients.

Table 2. Morphological traits of *Pseudotolithus elongatus* across climate zones

Morphological trait	**Low-salinity zone**	**Medium-salinity zone**	**High-salinity zone**	***P*-value**
Total length (cm)	32.5 ± 2.8^{a}	34.8 ± 3.1^{a}	36.2 ± 2.7^{b}	< 0.05
Body depth (cm)	8.5 ± 1.2^{a}	9.3 ± 1.5^{b}	10.1 ± 1.4^{c}	< 0.01
Caudal fin length (cm)	4.8 ± 0.6^{a}	5.1 ± 0.7^{a}	5.5 ± 0.8^{b}	< 0.05

Each value represents the Mean ± SD of three replicate samples. Means with different superscripts signify significant differences at $P<0.05$.

Impact of climate variables on morphological traits

The results demonstrated a significant impact of climate variables on the morphological traits of *Pseudotolithus elongatus*. A strong positive correlation was observed between mean annual water temperature and body depth, with the regression analysis yielding a high coefficient of determination ($R^2 = 0.87$), as shown in Fig. (2). This indicates that rising water temperatures are strongly associated with increased body depth, potentially reflecting adaptive responses to thermal stress in the estuarine environment.

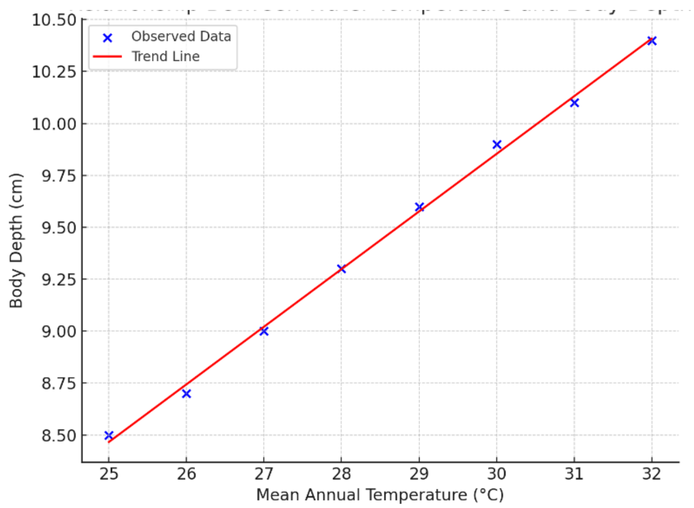

Fig. 2. Relationship between water temperature and body depth

Principal component analysis (PCA)

Principal component analysis revealed the primary contributors to morphological variation across the salinity zones. The first two principal components (PC1 and PC2) accounted for 68.4% of the total variance in the dataset, with PC1 alone explaining 47.2%. As summarized in Table (2), body depth (loading = 0.52) and caudal fin length (loading = 0.48) were heavily weighted on PC1, highlighting their significant sensitivity to salinity and temperature variations. The PCA biplot (Fig. 3) illustrated clear clustering of individuals from low-, medium-, and high-salinity zones, signifying distinct morphological adaptations driven by salinity gradients.

Table 2. Principal component loadings

Morphological trait	**PC1 (47.2%)**	**PC2 (21.2%)**
Total Length	0.36	-0.21
Body Depth	0.52*	0.34
Caudal Fin Length	0.48*	0.40

Note: Asterisked (*) values are significantly loaded.

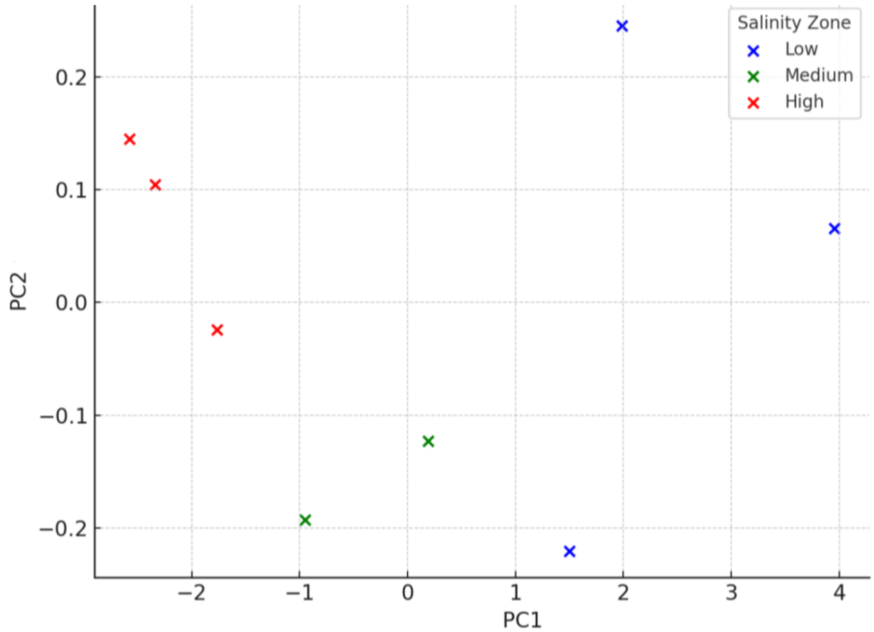

Fig. 3. PCA Biplot showing clusters of *Pseudotolithus elongatus* individuals from different salinity zones

Statistical modeling

Multiple linear regression analysis further elucidated the influence of climate variables on body depth, explaining 72% of the observed variance (Adjusted $R^2 = 0.72$, $P< 0.001$). As detailed in Table (3), salinity and temperature were significant positive predictors, with coefficients (β) of 0.08 ($P< 0.01$) and 0.14 ($P< 0.001$), respectively. Conversely, dissolved oxygen exhibited a modest but significant negative effect on body depth ($\beta = -0.03$, $P = 0.045$). These findings emphasize the significant role of climate-induced changes in environmental conditions on the morphological plasticity of *P. elongatus*. Elevated salinity and temperature were particularly influential, likely driving phenotypic adjustments to enhance swimming efficiency, foraging, and survival. The negative effect of dissolved oxygen may reflect metabolic constraints under hypoxic conditions, further highlighting the complexity of environmental pressures shaping morphological traits in estuarine habitats.

Table 3. Regression coefficients for body depth

Predictor	**Coefficient (β)**	**Standard error**	***P*-value**
Salinity (ppt)	0.08	0.02	< 0.01
Temperature (°C)	0.14	0.04	< 0.001
Dissolved Oxygen (mg/L)	-0.03	0.01	0.045

DISCUSSION

The findings of this study provide insights into the impact of climate change on the morphological adaptation of *Pseudotolithus elongatus* in the Cross River Estuary, highlighting the species' capacity for phenotypic plasticity under varying environmental stressors. Morphological traits such as body depth and caudal fin length were significantly influenced by salinity and temperature, suggesting an adaptive response to optimize swimming efficiency and buoyancy in changing aquatic environments over a 12-month period. Although climate change often spans decades, this period was chosen to provide a snapshot of the species' short-term responses to fluctuating conditions. While longer-term studies are essential for understanding gradual adaptations to climate change, the one-year duration allowed us to assess the immediate effects of temperature extremes and altered salinity patterns on the morphological traits of *P. elongatus*. This approach was particularly useful in the context of climate change, which is already causing noticeable shifts in environmental conditions that can have immediate effects on estuarine species.

Morphological adaptation to environmental changes

The observed increase in body depth and caudal fin length among *Pseudotolithus elongatus* individuals in higher salinity zones reflects distinct morphological adaptations to varying environmental conditions. These findings align with **Bshary and Triki (2022)**, who reported that fish species adapt morphologically to enhance hydrodynamic efficiency when exposed to environmental stressors, such as salinity and water turbulence. Specifically, deeper-bodied fish with larger caudal fins in high-salinity zones likely experience improved stability and propulsion in the face of stronger tidal currents, enabling them to optimize foraging and evade predators.

The positive correlation between water temperature and body depth ($R^2 = 0.87$) further supports the hypothesis that rising temperatures can drive morphological shifts in estuarine fish. This finding corroborates **De Souza *et al*. (2023)**, who demonstrated similar thermal-induced adaptations in other estuarine species. Such changes may reflect broader physiological adjustments to mitigate increased metabolic demands and thermal stress. These adaptations are critical for survival in transitional environments where temperature fluctuations and salinity gradients pose significant ecological challenges.

Sensitivity of morphological traits to climate variables

The principal component analysis (PCA) identified body depth and caudal fin length as the most sensitive morphological traits, collectively accounting for 47.2% of the total variance. These traits have been recognized in earlier studies as essential for hydrodynamic adaptation, as highlighted by **Bonamour *et al*. (2019)**. Their research demonstrated the importance of body shape and fin structure for maintaining mobility and foraging efficiency under changing hydrodynamic conditions. While **Bonamour *et al*. (2019)** primarily focused on temperate species, the present study extends these insights to tropical ecosystems, providing novel evidence of localized responses to salinity and temperature gradients.

In contrast to findings from temperate environments, tropical species such as *Pseudotolithus elongatus* exhibit unique adaptation strategies driven by the interplay of salinity, temperature, and dissolved oxygen. These distinctions underscore the importance of conducting region-specific studies to capture the nuances of biodiversity responses to climate change.

Implications for fisheries management

The morphological changes documented in this study have significant implications for the management and conservation of *Pseudotolithus elongatus* populations. Variations in body shape and fin structure can directly influence swimming performance, foraging efficiency, and habitat utilization. These adaptations may lead to shifts in the spatial distribution and abundance of the species, complicating efforts to sustain fisheries reliant on predictable catch patterns.

The potential redistribution of fish populations due to altered salinity and temperature regimes is particularly concerning for artisanal fisheries in the Cross River Estuary, where access to fishing grounds is often limited. **Cheung *et al*. (2013)** highlighted similar challenges, noting that climate-driven shifts in fish populations could render traditional fishing practices less effective. The findings of this study therefore emphasize the need for adaptive fisheries management strategies that incorporate climate variables into stock assessments and exploitation models.

This study also builds upon the earlier work of **Mahe *et al*. (2024)**, who assessed growth of *Pseudotolithus elongatus* in West African waters but did not explore the role of climate-induced morphological changes. By integrating climate variables into the analysis, the present study provides a more comprehensive understanding of how environmental stressors influence the species' phenotype, thereby addressing critical gaps in the existing literature.

Broader implications and future directions

While the findings align with the general consensus that climate change impacts fish morphology **(Izzo *et al*., 2018)**, this study uniquely emphasizes the role of localized stressors, such as salinity gradients, in tropical estuarine environments. These distinctions highlight the need for further region-specific studies to elucidate the complex interplay of global and local environmental changes on aquatic biodiversity.

Future research should explore the genetic basis of these morphological adaptations, examining whether observed changes are heritable or solely phenotypic responses to environmental conditions. Additionally, long-term monitoring of *Pseudotolithus elongatus* populations is essential to assess the persistence of these adaptations under projected climate scenarios. Such efforts will be crucial for developing robust conservation and management strategies to safeguard estuarine fisheries in the face of ongoing climate change.

CONCLUSION

This study reveals significant morphological adaptations of *Pseudotolithus elongatus* to spatial and temporal variations in salinity and temperature in the Cross River Estuary, highlighting the species' phenotypic plasticity in response to climate change-induced environmental stressors. Key traits, such as body depth and caudal fin length, showed significant correlations with environmental variables, demonstrating their role in enhancing survival and ecological fitness. These findings underscore the importance of adaptive morphological changes in maintaining population resilience under changing climatic conditions. Future management strategies should integrate continuous monitoring of environmental parameters and adaptive responses in estuarine fish populations to support sustainable fisheries and ecosystem conservation in the face of accelerating climate change.

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