Original Article

Caudal fin as a proxy for dorsal muscle for nutrient enrichment monitoring using stable isotope analysis: the case of *Gerres filamentosus* and *G. oyena* from mangrove creeks of Tanzania

Blandina R. Lugendo[1,*], Mathias M. Igulu[2,3], Masumbuko L. Semba[4], Ismael A. Kimirei[2]

[1] Department of Aquatic Sciences and Fisheries, University of Dar es Salaam, PO Box 60091, Dar es Salaam, Tanzania

[2] Tanzania Fisheries Research Institute, PO Box 9750, Dar es Salaam, Tanzania

[3] Western Indian Ocean Marine Science Association (WIOMSA), P.O. Box 3298, Zanzibar

[4] Nelson Mandela African Institution of Science and Technology, P.O. Box 447 Arusha, Tanzania

Western Indian Ocean JOURNAL OF Marine Science

Open access

Citation:
Lugendo B, Igulu MM, Semba ML, Kimirei IA (2022) Caudal fin as a proxy for dorsal muscle for nutrient enrichment monitoring using stable isotope analysis: the case of Gerres filamentosus and G. oyena from mangrove creeks of Tanzania. WIO J Mar Sci 21(2): pp-pp [doi: 10.4314/wiojms.v21i2.7]

Received:
May 26, 2022

Accepted:
November 9, 2022

Published:
February 27, 2023

*** Corresponding author:**
blugendo@udsm.ac.tz

Abstract

The use of fish dorsal muscles in stable isotope studies, which is an invasive method that results in fish deaths, limits their applicability for rare and endangered fish species, as well as when large sample sizes and replicates are required, prompting research into feasible non-lethal sampling methods. The possibility of employing fin clippings (a non-invasive approach) was investigated as a proxy for dorsal muscle in nutrient pollution monitoring studies using two common mangrove fish species, namely *Gerres filamentosus* and *G. oyena*, which are known to spend their early life stages primarily within mangroves. The dorsal muscles and caudal fin tissues of fish from the mangrove creeks of Kunduchi and Mbegani, Tanzania, were examined for ^{13}C and ^{15}N signatures. Dorsal muscles from Kunduchi (mean SD: ^{13}C = -16.8 ± 2.86, ^{15}N = 9.34 ± 1.15) were more enriched than from Mbegani (mean SD: ^{13}C = -18.60 ± 2.11, ^{15}N = 7.27 ± 1.09), and this enrichment was consistent across the two studied species. Caudal fins indicated similar enrichment trends. Fin tissue stable isotope values explained between 62% and 87% of dorsal muscle ^{13}C and between 89% and 98% of dorsal muscle ^{15}N variability. These findings support the use of fin-clipping as a non-lethal proxy for stable isotope analysis of the studied species for nutrient enrichment, and additional research into non-lethal sampling methods is recommended.

Keywords: mangrove fish, coastal pollution, western Indian Ocean, fin clipping, stable isotopes, non-lethal sampling.

Introduction

Mangroves provide critical habitats for a diverse range of fish species, the majority of which are commercially valuable. They are also important as nurseries for many coral reef fishes (Bradley *et al.*, 2019; Igulu *et al.*, 2014; Kimirei *et al.*, 2016; Lugendo *et al.*, 2006; Lugendo *et al.*, 2007; Nagelkerken *et al.*, 2008), contributing significantly to artisanal coral reef fisheries when assessed at the species level (Kimirei *et al.*, 2013; Nakamura *et al.*, 2008). Nonetheless, mangroves are disappearing globally owing to both natural and human causes (Alongi, 2014; Duke *et al.*, 2007; FAO, 2007), threatening their ability to provide ecosystem goods and services (Abrantes *et al.*, 2019; Guannel *et al.*, 2016; Kimirei *et al.*, 2016).

Most Indo-Pacific mangrove habitats have large tidal ranges, which affect tidal movement of large amounts

of seawater and fish between neighbouring habitats, reducing their value as nursery, shelter, and feeding habitats (Faunce and Layman, 2009; Nagelkerken, 2009; Nagelkerken and Velde, 2004) and fisheries (Blaber, 2009). Mangroves may potentially become functionally extinct as a result of degradation, with unexpected consequences for the viability of coastal artisanal fishing, which is a lifeline for many coastal inhabitants (Kimirei *et al.*, 2016; Staehr *et al.*, 2018).

Coastal pollution and eutrophication induced by land-based point and non-point sources are just two of the many threats to mangroves and associated habitats (seagrass beds and coral reefs), particularly on urbanised coasts (Boesch, 2019; Oczkowski *et al.*, 2014; Vikas and Dwarakish, 2015; Xiao *et al.*, 2017). Nutrient input into mangroves and estuaries, as well as other forms of chemical pollution are threatening the mangrove ecosystems and surrounding ecosystems (Asmala *et al.*, 2019; Staehr *et al.*, 2017; Staehr *et al.*, 2018). For example, coastal eutrophication can cause proliferation of harmful algal blooms (HAB) and deoxygenation of coastal waters (Breitburg *et al.*, 2018; Oczkowski *et al.*, 2014), which can lead to the deterioration of ecosystem integrity, loss of critical habitats (coral reefs and seagrasses), and changes in ecological structure (Howarth *et al.*, 2011). Domestic, industrial and agricultural effluents, as well as wastes from aquaculture operations, are example of anthropogenic nitrogen and phosphorus contamination (Lovelock *et al.*, 2009). While mangroves are known to filter nutrients and other forms of pollution, protecting adjacent ecosystems from pollution, excessive pumping of nutrients and pollutants into these wetlands may reach a tipping point, causing die-offs and a critical decimation of their protective and provisioning capacities/services (Selkoe *et al.*, 2015; Serrao-Neumann *et al.*, 2016; Watson *et al.*, 2018). As a result, monitoring nutrient pollution and accumulation, as well as other types of mangrove disturbances, is crucial.

Nutrient analysis and long-term monitoring programs can be used to monitor coastal pollution. Traditional approaches, particularly spectrophotometric analysis, have long been used to assess and monitor nutrient inputs into aquatic ecosystems (Parsons *et al.*, 1984). While this is feasible and can easily document long-term changes in nutrients inputs and accumulation in coastal waters and ecosystems, it may be costly and unsustainable, particularly for resource-poor countries (as it may require regular sample collection), where investment in monitoring programmes may not be a priority. In addition, this technique only reveals the present condition, with the possibility of missing nutrient input events that occurred weeks or months earlier (Gearing, 1991), thus needing regular monitoring. As an alternative, stable isotope analysis may be used in studying nutrient pollution to infer enrichment patterns from a few samples that are relatively easy and cheap to replicate over time (Carmichael *et al.*, 2004; Teichberg *et al.*, 2010).

Although other organisms such as plants, sediment and water samples are also used (Cole *et al.*, 2004; Costanzo *et al.*, 2001; Costanzo *et al.*, 2005; Gritcan *et al.*, 2016; Lugendo and Kimirei, 2021; Savage, 2005), fish and shellfish tissues have been routinely used to examine nitrogen enrichment in coastal waters. Carbon stable isotopes have also been investigated recently to serve the same purpose as nitrogen isotopes (Oczkowski *et al.*, 2020).

Despite the widespread use of fish in ecological studies using the stable isotopes approach, the use of dorsal muscles extracted from fish - an invasive method that results in the death of the specimens, limits their applicability in species of concern such as rare and endangered species, or when large sample sizes and replicates are required. This has prompted research into plausible non-lethal sampling methods that may be used as a proxy for dorsal muscle, with various studies selecting fish fins, fish scales, mucous, liver, plasma, and red blood cells as candidates (Boardman *et al.*, 2022; Church *et al.*, 2009; Hayden *et al.*, 2015; Hayden *et al.*, 2017; Matley *et al.*, 2016; McIntosh and Reid, 2021; Tronquart *et al.*, 2012).

The overarching objective of the current study was to investigate the possibility of using fin clippings as a non-invasive method and a proxy for dorsal muscle in nitrogen pollution monitoring studies in coastal habitats of Tanzania, and the western Indian Ocean (WIO) region in general. This was achieved by comparing the levels of nitrogen and carbon stable isotopes in dorsal muscle and caudal fin tissues of two common mangrove fish species (*Gerres filamentosus* and *G. oyena*). Furthermore, the purpose of this study was to compare the nitrogen enrichment levels of fishes collected from polluted (Kunduchi, Dar es Salaam) and relatively pristine (Mbegani, Bagamoyo) mangrove habitats in Tanzania, and to determine whether or not the nitrogen enrichment in the two species is consistent across the two mangrove areas. There is a dearth of such research in the WIO, but it is particularly lacking in Tanzania.

Materials and methods

Study area

This study was carried out in Tanzanian coastal waters in two mangrove-lined creeks, namely Kunduchi and Mbegani. Kunduchi is located along the coast of Dar es Salaam, about 20 km away from the Dar es Salaam City Centre, and prone to more pollution than Mbegani, which is located along the Bagamoyo coast, about 50 km away from the Dar es Salaam City (Fig. 1). Several species of mangroves occur at Kunduchi with *Avicennia marina*, *Ceriops tagal* and *Rhizophora mucronata* dominating. On the other hand, Mbegani consists of a strip of mangroves (approximately 420 m wide) of mainly *Sonneratia alba*, mixed with *R. mucronata*, *A. marina,* and *Bruguiera gymnorhiza* (Kimirei *et al.*, 2011). Both sites are characterised by large tidal creeks, which never empty completely, even during low spring tides. At the landward side of Mbegani creek, there is a stream (Nyanza River), a potential source of freshwater leading into the mangrove forest during the rainy season. Data were collected here during the dry season.

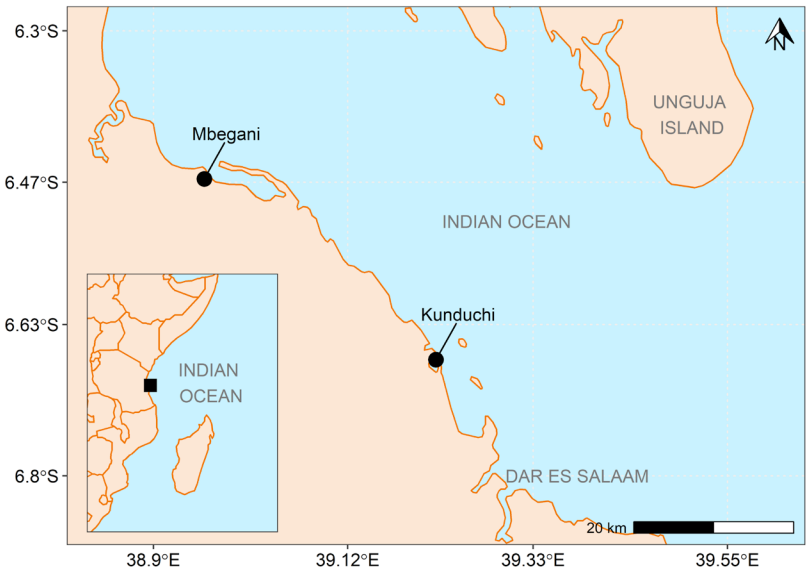

Figure 1. Map showing the study sites.

Sampling design

A total of 425 individual fish were collected using a seine net from the Kunduchi and Mbegani mangrove creeks, during low tide between January and December 2009. In the field, the fish samples were put in a cool box and later frozen at -20 ˚C pending sorting into species, preparation and analysis.

Sample preparation and stable isotope analysis

The collected fishes were sorted into species, and a total of 23 (6 *Gerres filamentosus* and 17 *G. oyena*) from Mbegani and 24 (4 *G. filamentosus* and 20 *G. oyena*) from Kunduchi were selected. The two species were selected primarily based on their life histories and their presence in the catches from both sites. The two species are known to spend their early lives primarily within mangroves (Mwandya *et al.*, 2009). The size (Total Length) of *G. filamentosus* and *G. oyena* from the two sites ranged between 4.6 and 10 cm, which represents juvenile stages of the two species, respectively, the stage in which they reside in mangroves (Mwandya *et al.*, 2009). A total of 94 tissue samples (47 dorsal muscle tissues and 47 caudal fin tissues) were collected from the two species. Samples were then dried at 70˚C for 48 h and ground to a homogeneous powdery mixture. A pre-determined sample of known weight was placed in ultra-pure tin capsules and combusted in a CHN Elemental Analyser from Carlo Erba® (Thermo group), interfaced with a continuous flow isotope ratio mass-spectrometer, the DeltaPlus from Thermo Finnigan, Bremen, Germany, and the stable carbon and nitrogen isotopes of the selected fishes were measured. The reference gasses were calibrated with the International Atomic Energy Agency (IAEA) reference standards, IAEA-N-2 and IAEA-CH-6.

Data analysis

The data ($\delta^{13}C$ and $\delta^{15}N$ values) of fish tissues between sites, species and tissues were tested for normality

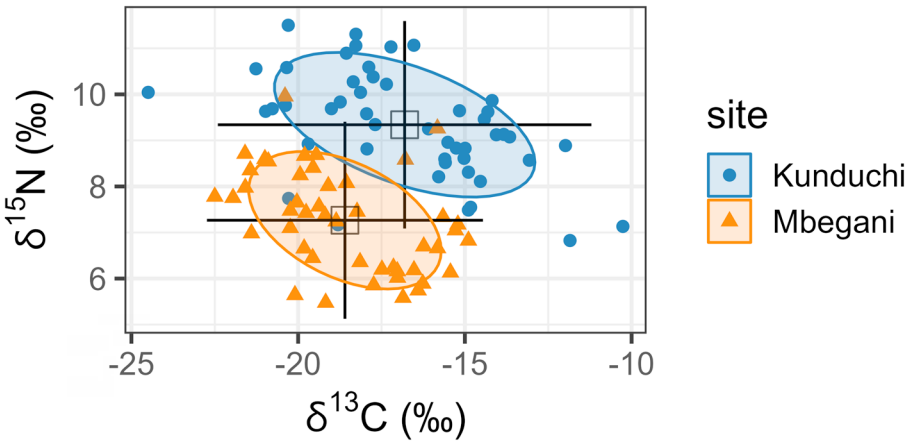

Figure 2. Stable carbon and nitrogen isotope enrichment signatures of fishes collected from Kunduchi (n=48) and Mbegani (n=46). The data for each site include both species and tissue types. Eclipses show the direction of mean values.

using the Shapiro – Wilk test. Measures of central tendencies and descriptive statistics (mean, media, standard deviations, and standard error of mean) were computed and compared across sites, species, and tissues. To test for differences between sites, the carbon and nitrogen stable isotopes data of muscle and fin tissues were pooled across fish species and sites. A non-parametric Wilcoxon Rank Sum test was used to test whether the median of the stable carbon and nitrogen isotope of the combined fish species differed between sites. A two-way ANOVA with interaction was used to test if the enrichment in stable carbon and nitrogen isotopes of *Gerres filamentosus* and *G. oyena* were consistent between the two sites. Comparisons of stable isotopes between tissues for species and sites were performed using the independent samples t-tests on robust location measures (Yuen t-test) for trimmed means (Yuen, 1974). The Yuen test was chosen rather than the student t-test because it is a robust parametric test for the data that violates normal distribution and equal variance rules. Finally, correlation analysis was used to compare stable isotope data of dorsal muscle and fin tissues to elucidate whether fin clips can be used as a proxy for dorsal muscle of the two species for monitoring nutrient pollution in coastal waters of Tanzania. All analyses and plotting were carried out in R programming language (R Core Team, 2020).

Results

Comparison of stable isotopes (δ15N and δ13C) of fishes between sites

The mean stable isotope signatures of the pooled data of both fish species from Kunduchi were more enriched with mean (±SD) $\delta^{13}C$ and $\delta^{15}N$ values of -16.81 ± -2.86‰ and 9.34 ± 1.15‰, respectively (Fig. 2), than those from Mbegani, which were appreciably depleted both for $\delta^{13}C$ (-18.60 ± 2.11) and $\delta^{15}N$ (7.27 ± 1.09) (Fig. 2). The stable isotope signatures formed

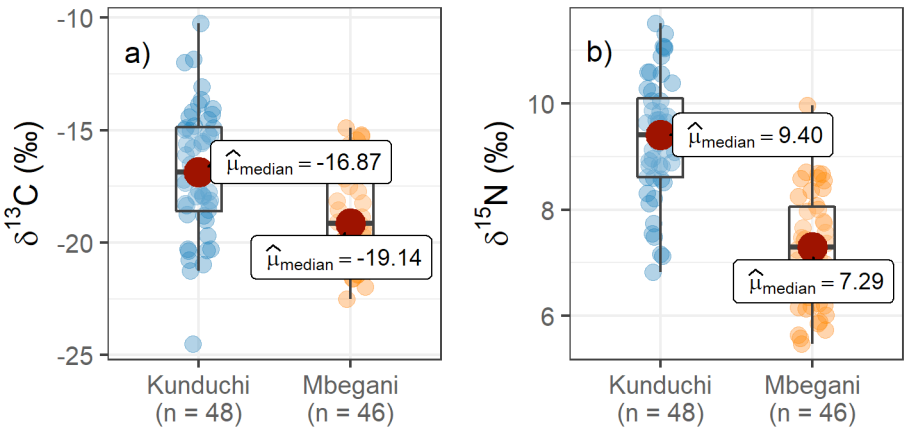

Figure 3. Comparison of a) $\delta^{13}C$ and b) $\delta^{15}N$ stable isotope signatures of fishes between Kunduchi and Mbegani mangroves.

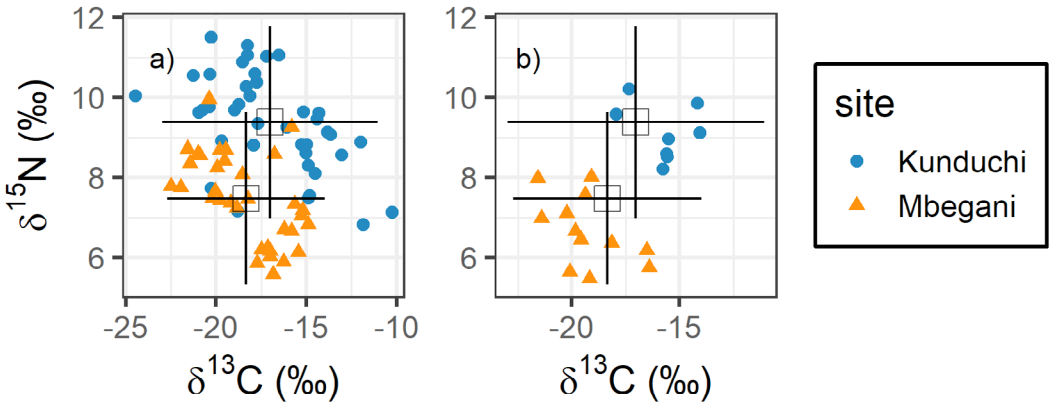

Figure 4. Comparison of stable isotope variation in tissues of a) *G. oyena* (n=74) and b) *G. filamentosus* (n=20) at Kunduchi and Mbegani.

distinct groups as an indication of enrichment status (Fig. 2). The median $\delta^{13}C$ signature was -16.87‰ at Kunduchi while it was -19.14‰ at Mbegani (Wilcoxon rank sum test, W = 1544, p < 0.05, Fig. 3a). Similarly, Kunduchi had more enriched $\delta^{15}N$ values than at Mbegani, where the median value of nitrogen isotope was 9.40‰ at Kunduchi and 9.29‰ at Mbegani (W = 1988.5, p < 0.05, Fig. 3b).

Comparison between species

The $\delta^{15}N$ and $\delta^{13}C$ signatures of *G. oyena* and *G. filamentosus* were compared to test for the stability of stable isotope enrichment pattern between species without taking tissue types into account. There were no significant differences in stable isotope enrichment between species ($F_{(1,183)}$ = 2.61; p = 0.108) indicating a consistent enrichment pattern between them. However, the $\delta^{15}N$ and $\delta^{13}C$ signatures of the two species were consistently more enriched at Kunduchi than at Mbegani ($F_{(1,183)}$ = 47.60; p < 0.001; Fig. 4), indicating that the observed pattern is stable across species and sites. The mean (±SD) of $\delta^{15}N$ and $\delta^{13}C$ signatures for *G. oyena* at Kunduchi were 9.38 ± 1.22 and -17.02 ± 3.04, respectively, while at Mbegani they were 7.47 ± 1.10 and -18.35 ± 2.23, respectively. For *G. filamentosus*, the mean (±SD) of $\delta^{15}N$ and $\delta^{13}C$ signatures for Kunduchi were 9.13 ± 0.70 and -15.75 ± 1.35, respectively, and 6.68 ± 0.87 and -19.29 ± 1.62, respectively, for Mbegani (Fig. 4).

Comparison between muscle and fin tissue

The carbon stable isotope values of muscle tissue (-16.2 ± 2.4‰) were significantly more enriched than those of fin tissue (-16.9 ± 2.1‰) (Yuen t-test, $t_{(65.82)}$ = 2.246, p = 0.028) when samples were pooled for species and sites. The nitrogen stable isotope values, although enriched in muscle tissue (9.56 ± 1.9‰), were barely different from the fin tissue values (8.8 ± 1.9‰) (Yuen t-test, $t_{(65.11)}$ = 1.946, p = 0.056). On an individual species level, the $\delta^{13}C$ and $\delta^{15}N$ values were generally more enriched in muscle than fin tissue for all species (Fig. 5). However, the difference were significant in carbon isotope (Yuen t-test, $t_{(43.23)}$ = 2.452, p = 0.018)

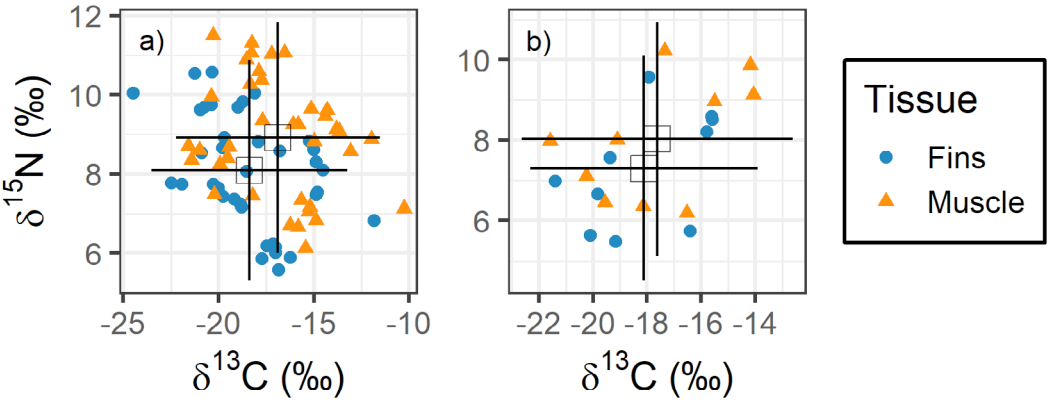

Figure 5. The $\delta^{13}C$ and $\delta^{15}N$ signatures in dorsal muscle and caudal fin tissues of fish species for a) *G. oyena* (n=37 for fin tissues and 37 for muscle tissues) and b) *G. filamentosus* (n=10 for fin tissues and 10 for muscle tissues).

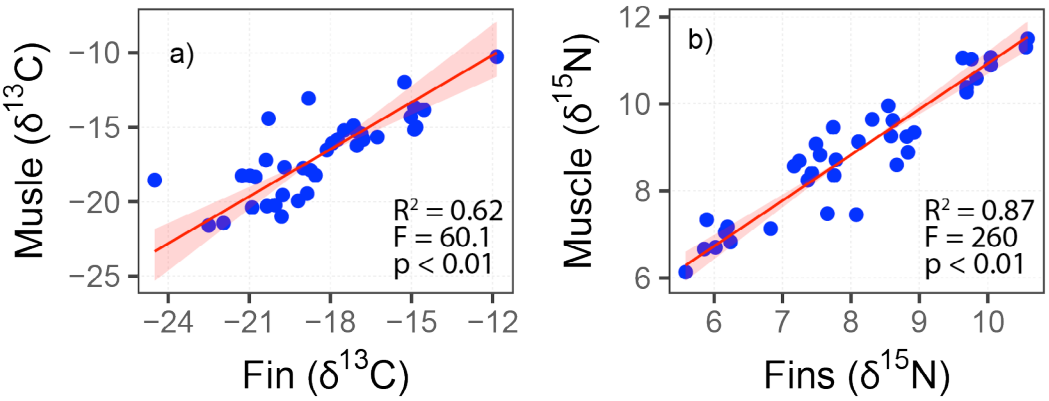

Figure 6. Correlation of a) δ^{13}C and b) δ^{15}N signatures between dorsal muscle and caudal fin tissues of *G. oyena* combined for all sites (n=37).

but not for nitrogen ($t_{(43.841)}$ = 1.880, p = 0.067; Fig. 5a). There was no significant difference in values of carbon ($t_{(17.46)}$ = -0.467, p = 0.646) and nitrogen ($t_{(17.97)}$ = -1.119, p = 0.278) stable isotopes between muscle and fin tissues for *G. filamentosus* (Fig. 5b).

Fin-clip as a proxy of muscle δ13C and δ15N

The stable carbon and nitrogen isotopes of *G. oyena* (Fig. 6) and *G. filamentosus* (Fig. 7), combined for both sites, were significantly correlated between dorsal muscle and caudal fin tissues. While δ^{13}C values of fin tissue explained 62% of stable isotope variations in dorsal muscle tissue of *G. oyena*, δ^{15}N values explained 87% of the variations (Fig. 6). For *G. filamentosus*, δ^{13}C values of fin tissue explained 89% of the variations and 98% of variation in δ^{15}N in the dorsal muscle values (Fig. 7).

Discussion

This study found that stable nitrogen isotope (δ^{15}N) ratios were more enriched in fish samples caught in the Kunduchi mangroves as compared to those collected in Mbegani. While the nitrogen isotope ratio was 10‰ at Kunduchi, and 7‰ at Mbegani, the δ^{15}N value at Kunduchi was a magnitude higher than the value of 9‰ measured at the same location in 2005 (Kruitwagen *et al.*, 2006). The high δ^{15}N values at Kunduchi indicate signs of nutrients enrichment (Kruitwagen *et al.*, 2006; Lugendo *et al.*, 2007; McClelland *et al.*, 1997; Samper-Villarreal *et al.*, 2018). Similar δ^{15}N enrichment observations have been reported in the Mtoni Kijichi mangroves (Kruitwagen *et al.*, 2006; Kruitwagen *et al.*, 2008), where values as high as 13‰ were measured in mudskippers (Kruitwagen *et al.*, 2006), and mangrove snails (Kimirei *et al.*, unpublished data). Both Kunduchi and Mtoni Kijichi mangroves are located in areas with high population densities (NBS, 2013). Also, Mtoni Kijichi receives large quantities of industrial effluents (Kruitwagen *et al.*, 2006; Kruitwagen *et al.*, 2008; Machiwa, 1992; Machiwa, 2010). The Dar es Salaam City has poor waste disposal facilities, which further contributes to the coastal pollution problem (Kimirei *et al.*, 2016).

Like δ^{15}N, the stable carbon isotope (δ^{13}C) values for fish from Kunduchi were slightly enriched when compared to fish from Mbegani. Both *G. oyena* and

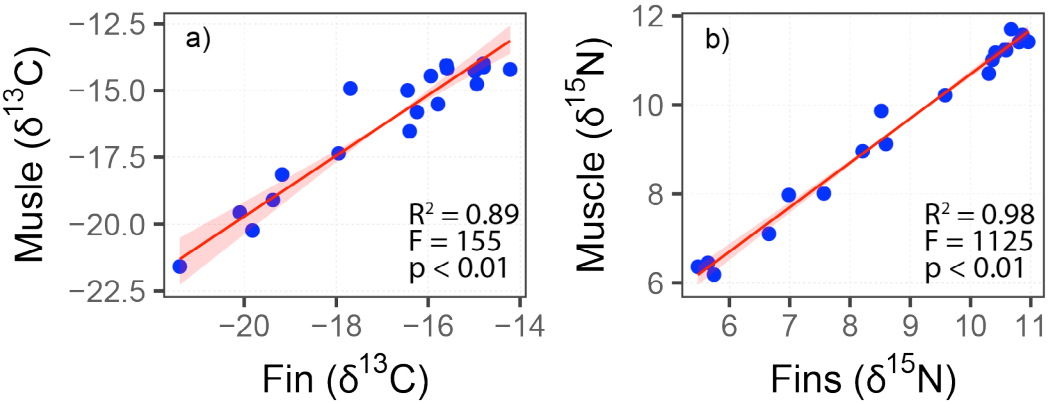

Figure 7. Corelation of a) δ^{13}C and b) δ^{15}N signatures between dorsal muscle and caudal fin tissues of *G. filamentosus* combined for all sites (n = 20).

G. filamentosus are generalists (Mavuti *et al.*, 2004), and share various carbon sources at Kunduchi, as indicated by the highly mixed $\delta^{13}C$ signatures (see Fig. 3a). However, the $\delta^{13}C$ signatures were different between *G. oyena* and *G. filamentosus* at Mbegani, with $\delta^{13}C$ isotopes enriched in *G. oyena* in both muscle and fin tissues (see Fig. 3b). These results may indicate that the two species have significantly different carbon sources at Mbegani, although they have been reported to feed in similar environments (Lugendo *et al.*, 2007).

When compared to Mbegani, the fishes collected from the Kunduchi mangrove creek appear to have a substantially higher level of nutrient enrichment, which is indicated by the high $\delta^{15}N$ ratio. While Kunduchi was considered relatively pristine in other studies (Kruitwagen *et al.*, 2008), this study indicates that during the sampling time, it was becoming increasingly polluted (Jiang *et al.*, 2019; McClelland and Valiela, 1998; McClelland *et al.*, 1997). The increased enrichment in Kunduchi may be due to increasing human population, industrial and domestic effluents, and urban agriculture, which utilize inorganic fertilizers to boost production. Mangroves are increasingly being polluted (Machiwa, 1992; Machiwa, 2010), perturbed and cleared (Ajai and Chauhan, 2017), which decimates the value they play in terms of ecosystem services (Kimirei *et al.*, 2016). While the data analysed in the current study are based on samples collected a decade ago, it has significance in assessing the role of population growth and anthropogenic pollution on nutrients pollution in mangroves (see Lugendo and Kimirei, 2021).

On an individual species-level, $\delta^{15}N$ values were always more enriched in muscle than in fin tissues while the opposite was true for the $\delta^{13}C$ values which were higher in fins than in muscles. Similar observations were made for *Oncorhynchus tshawytscha* and *O. mykiss* (Sanderson *et al.*, 2009). While it is beyond the scope of this study, the differences in isotopic enrichment between muscle and fin tissues may be explained by the abundance of both essential and non-essential amino acids for $\delta^{15}N$, and lipids for $\delta^{13}C$ (Pinnegar and Polunin, 1999; Sanderson *et al.*, 2009). Nonetheless, it was found that both carbon and nitrogen stable isotope signatures were highly correlated between muscle and fin tissues of the fish species examined. The nitrogen isotopes of fins explained >80% of the variations in stable isotope values of muscle tissue. These findings indicate that fin-clipping can be used as a reliable non-lethal method for stable isotope analysis (SIA) of nitrogen enrichment for the studied fish species. Fin-clipping has been found to be especially useful in monitoring endangered species (Jardine *et al.*, 2011; Kelly *et al.*, 2006; Sanderson *et al.*, 2009; Valladares and Planas, 2012), as well as in situations requiring large sample sizes and replications (Sanderson *et al.*, 2009). Stable isotope analysis as a tool for monitoring nitrogen enrichment in coastal waters should be especially useful in countries with minimal financial resources to run long-term monitoring campaigns.

The findings of this study support the use of fin-clipping as a non-lethal proxy for stable isotope analysis for the fish species under consideration. Furthermore, this study found that the stable nitrogen and carbon isotope signatures of fish collected from Kunduchi mangrove creeks were more enriched than those collected from Mbegani, and this enrichment was consistent across the two studied species. The results of this study, the first in the WIO region to examine the non-lethal collection of fish tissues for use in stable isotope studies, are positive, and should encourage the use of fin clipping as an alternative to the extraction of dorsal muscle tissues in stable isotope studies involving fishes. It is also recommended that more research is done on non-lethal sampling techniques to include more species and tissue types.

Acknowledgments

We are grateful to Mr. Atta, Mr. Hassan Ramadhan, and Mr. Muhonda Yukundus for assistance during fieldwork and laboratory processing of the samples. The University of Dar es Salaam and the Tanzania Fisheries Research Institute (TAFIRI) are acknowledged for providing us with laboratory space and the time to conduct this study. The Stable Isotope analysis was done at the OEA Laboratories Limited, UK.

Funding: This work was supported by the Western Indian Ocean Marine Science Association (WIOMSA) through a MARG I grant [Contract No. 5/2008].

References

Abrantes KG, Sheaves M, Fries J (2019) Estimating the value of tropical coastal wetland habitats to fisheries: Caveats and assumptions. PloS One 14: e0215350 [https://doi.org/10.1371/journal.pone.0215350]

Ajai, Chauhan HB (2017) Mangrove inventory, monitoring, and health assessment. In: Finkl CW, Makowski C (eds) Coastal wetlands: Alteration and remediation. Springer International Publishing, Cham. pp 573-630 [https://doi.org/10.1007/978-3-319-56179-0_19]

Alongi DM (2014) Mangrove forests of Timor-Leste: Ecology, degradation and vulnerability to climate change. Mangrove ecosystems of Asia. Springer. pp 199-212 [https://doi.org/10.1007/978-1-4614-8582-7_9]

Asmala E, Gustafsson C, Krause-Jensen D, Norkko A, Reader H, Staehr PA, Staehr PA, Carstensen J (2019) Role of eelgrass in the coastal filter of contrasting Baltic Sea environments. Estuaries and Coasts 42: 1882-1895 [https://doi.org/10.1007/s12237-019-00615-0]

Blaber SJM (2009) Relationships between tropical coastal habitats and (offshore) fisheries. In: Nagelkerken I (ed) Ecological connectivity among tropical coastal ecosystems. Springer, Dordrecht, Netherlands. pp 533-564 [https://doi.org/10.1007/978-90-481-2406-0_15]

Boardman RM, Pinder AC, Piper AT, Roberts CG, Wright RM, Britton JR (2022) Non-lethal sampling for the stable isotope analysis of the critically endangered European eel *Anguilla anguilla*: how fin and mucus compare to dorsal muscle. Journal of Fish Biology: 1-5 [https://doi.org/10.1111/jfb.14992]

Boesch DF (2019) Barriers and bridges in abating coastal eutrophication. Frontiers in Marine Science 6: 123 [https://doi.org/10.3389/fmars.2019.00123]

Bradley M, Baker R, Nagelkerken I, Sheaves M (2019) Context is more important than habitat type in determining use by juvenile fish. Landscape Ecology 34: 427-442 [https://doi.org/10.1007/s10980-019-00781-3]

Breitburg D, Levin LA, Oschlies A, Gregoire M, Chavez FP, Conley DJ, Garcon V, Gilbert V, Gutierrez D, Isensee K, Jacinto GS, Limburg KE, Montes I, Naqvi SWA, Pitcher GC, Rabalais NN, Roman MR, Kenneth AR, Seibel BA, Telszewski M, Yasuhara M, Zhang J (2018) Declining oxygen in the global ocean and coastal waters. Science 359: eaam7240 [https://doi.org/10.1126/science.aam7240]

Carmichael RH, Annett B, Valiela I (2004) Nitrogen loading to Pleasant Bay, Cape Cod: application of models and stable isotopes to detect incipient nutrient enrichment of estuaries. Marine Pollution Bulletin 48: 137-143 [https://doi.org/10.1016/s0025-326x(03)00372-2]

Church MR, Ebersole JL, Rensmeyer KM, Couture RB, Barrows FT, Noakes DLG (2009) Mucus: a new tissue fraction for rapid determination of fish diet switching using stable isotope analysis. Canadian Journal of Fisheries and Aquatic Sciences 66: 1-5 [https://doi.org/10.1139/f08-206]

Cole ML, Valiela I, Kroeger KD, Tomasky GL, Cebrian J, Wigand C, McKinney RA, Grady SP, Carvalho da Silva MH (2004) Assessment of a $\delta^{15}N$ isotopic method to indicate anthropogenic eutrophication in aquatic ecosystems. Journal of Environmental Quality 33: 124-132 [https://doi.org/10.2134/jeq2004.1240]

Costanzo SD, O'Donohue MJ, Dennison WC, Loneragan NR, Thomas M (2001) A new approach for detecting and mapping sewage impacts. Marine Pollution Bulletin 42: 149-156 [https://doi.org/10.1016/S0025-326X(00)00125-9]

Costanzo SD, Udy J, Longstaff B, Jones A (2005) Using nitrogen stable isotope ratios (δ15N) of macroalgae to determine the effectiveness of sewage upgrades: changes in the extent of sewage plumes over four years in Moreton Bay, Australia. Marine Pollution Bulletin 51: 212-217 [https://doi.org/10.1016/j.marpolbul.2004.10.018]

Duke NC, Meynecke J-O, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F (2007) A world without mangroves? Science 317: 41-42 [https://doi.org/10.1126/science.317.5834.41b]

FAO (2007) The world's mangroves 1980–2005. FAO Forestry Paper 153. Rome. 77 pp

Faunce CH, Layman CA (2009) Sources of variation that affect perceived nursery function of mangroves. In: Nagelkerken I (ed) Ecological connectivity among tropical coastal ecosystems. Springer, Dordrecht, Netherlands. pp 401-421 [https://doi.org/10.1007/978-90-481-2406-0_11]

Gearing JN (1991) The study of diet and trophic relationships through natural abundance 13C. In: Coleman DC, Fry B (eds) Carbon isotope techniques. Academic Press, San Diego, CA. pp 201-218

Gritcan I, Duxbury M, Leuzinger S, Alfaro AC (2016) Leaf stable isotope and nutrient status of temperate mangroves aseEcological indicators to assess anthropogenic activity andrRecovery fromeEutrophication. Frontiers in Plant Science 7: 1922 [https://doi.org/10.3389/fpls.2016.01922]

Guannel G, Arkema K, Ruggiero P, Verutes G (2016) The power of three: Coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. PloS One 11: e0158094 [https://doi.org/10.1371/journal.pone.0158094]

Hayden B, Soto DX, Jardine TD, Graham BS, Cunjak RA, Romakkaniemi A, Linnansaari T (2015) Small tails tell tall tales – Intra-individual variation in the stable isotope values of fishf fin. PloS One 10: e0145154 [https://doi.org/10.1371/journal.pone.0145154]

Hayden B, Tongnunui S, Beamish FWH, Nithirojpakdee P, Cunjak RA (2017) Variation in stable-isotope ratios between fin and muscle tissues can alter assessment of resource use in tropical river fishes. Journal of Fish Biology 91: 574-586 [https://doi.org/10.1111/jfb.13368]

Howarth R, Chan F, Conley DJ, Garnier J, Doney SC, Marino R, Billen G (2011) Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Frontiers in Ecology and the Environment 9: 18-26 [https://doi.org/10.1890/100008]

Igulu MM, Nagelkerken I, Dorenbosch M, Grol MGG, Harborne AR, Kimirei IA, Mumby PJ, Olds AD, Mgaya YD (2014) Mangrove habitat use by juvenile reef fish: Meta-analysis reveals that tidal regime matters more than biogeographic region. PloS One 9: e114715 [https://doi.org/10.1371/journal.pone.0114715]

Jardine TD, Hunt RJ, Pusey BJ, Bunn SE (2011) A non-lethal sampling method for stable carbon and nitrogen isotope studies of tropical fishes. Marine and Freshwater Research 62: 83-90 [https://doi.org/10.1071/MF10211]

Jiang Q, He J, Wu J, Hu X, Ye G, Christakos G (2019) Assessing the severe eutrophication status and spatial trend in the coastal waters of Zhejiang province (China). Limnology and Oceanography 64: 3-17 [https://doi.org/10.1002/lno.11013]

Kelly MH, Hagar WG, Jardine TD, Cunjak RA (2006) Nonlethal sampling of Sunfish and Slimy Sculpin for stable isotope analysis: how scale and fin tissue compare with muscle tissue. North American Journal of Fisheries Management 26: 921-925 [https://doi.org/10.1577/M05-084.1]

Kimirei IA, Nagelkerken I, Griffioen B, Wagner C, Mgaya YD (2011) Ontogenetic habitat use by mangrove/seagrass-associated coral reef fishes shows flexibility in time and space. Estuarine Coastal and Shelf Science 92: 47-58 [https://doi.org/10.1016/j.ecss.2010.12.016]

Kimirei IA, Nagelkerken I, Mgaya YD, Huijbers CM (2013) The mangrove nursery paradigm revisited: Otolith stable isotopes support nursery-to-reef movements by Indo-Pacific fishes. PloS One 8: e66320 [https://doi.org/10.1371/journal.pone.0066320]

Kimirei IA, Igulu MM, Semba M, Lugendo BR (2016) Small estuarine and non-estuarine mangrove ecosystems of Tanzania: Overlooked coastal habitats? In: Diop S, Scheren P, Ferdinand Machiwa J)(eds) Estuaries: A lifeline of ecosystem services in the western Indian Ocean. Springer International Publishing, Cham. pp 209-226 [https://doi.org/10.1007/978-3-319-25370-1_13]

Kruitwagen G, Hecht T, Pratap HB, Wendelaar Bonga SE (2006) Changes in morphology and growth of the mudskipper (*Periophthalmus argentilineatus*) associated with coastal pollution. Marine Biology 149: 201-211 [https://doi.org/10.1007/s00227-005-0178-z]

Kruitwagen G, Pratap HB, Covaci A, Wendelaar Bonga SE (2008) Status of pollution in mangrove ecosystems along the coast of Tanzania. Marine Pollution Bulletin 56: 1022-1031 [https://doi.org/10.1016/j.marpolbul.2008.02.018]

Lovelock CE, Ball MC, Martin KC, Feller I (2009) Nutrient enrichment increases mortality of mangroves. PloS One 4: e5600 [https://doi.org/10.1371/journal.pone.0005600]

Lugendo BR, Nagelkerken I, Van Der Velde G, Mgaya YD (2006) The importance of mangroves, mud and sand flats, and seagrass beds as feeding areas for juvenile fishes in Chwaka Bay, Zanzibar: gut content and stable isotope analyses. Journal of Fish Biology 69: 1639-1661 [https://doi.org/10.1111/j.1095-8649.2006.01231.x]

Lugendo BR, Nagelkerken I, Kruitwagen G, Van Der Velde G, Mgaya YD (2007) Relative importance of mangroves as feeding habitats for fishes: a comparison between mangrove habitats with different settings. Bulletin of Marine Science 80: 497-512

Lugendo BR, Kimirei IA (2021) Anthropogenic nitrogen pollution in mangrove ecosystems along Dar es Salaam and Bagamoyo coasts in Tanzania. Marine Pollution Bulletin 168: 112415 [https://doi.org/10.1016/j.marpolbul.2021.112415]

Machiwa JF (1992) Anthropogenic pollution in the Dar es Salaam harbour area, Tanzania. Marine Pollution Bulletin 24: 562-567 [https://doi.org/10.1016/0025-326X(92)90709-F]

Machiwa JF (2010) Coastal marine pollution in Dar es Salaam (Tanzania) relative to recommended environmental quality targets for the western Indian Ocean. Western Indian Ocean Journal of Marine Science 9: 17-30

Matley JK, Fisk AT, Tobin AJ, Heupel MR, Simpfendorfer CA (2016) Diet-tissue discrimination factors and turnover of carbon and nitrogen stable isotopes in tissues of an adult predatory coral reef fish, *Plectropomus leopardus*. Rapid Communications in Mass Spectrometry 30: 29-44 [https://doi.org/10.1002/rcm.7406]

Mavuti KM, Nyunja JA, Wakwabi EO (2004) Trophic ecology of some common juvenile fish species in Mtwapa Creek, Kenya. Western Indian Ocean Journal of Marine Science 3: 179-187 [https://doi.org/10.4314/wiojms.v3i2.28460]

McClelland JW, Valiela I, Michener RH (1997) Nitrogen-stable isotope signatures in estuarine food webs: A record of increasing urbanization in coastal watersheds. Limnology and Oceanography 42: 930-937 [https://doi.org/10.4319/lo.1997.42.5.0930]

McClelland JW, Valiela I (1998) Linking nitrogen in estuarine producers to land-derived sources. Limnology and Oceanography 43: 577-585 [https://doi.org/10.4319/lo.1998.43.4.0577]

McIntosh LM, Reid MA (2021) Fish fins as a non-lethal alternative to muscle tissue in stable isotope studies of food webs in an Australian river. Marine and Freshwater Research 72: 838-847 [https://doi.org/10.1071/MF20211]

Mwandya AW, Gullström M, Öhman MC, Andersson MH, Mgaya YD (2009) Fish assemblages in Tanzanian mangrove creek systems influenced by solar salt farm constructions. Estuarine, Coastal and Shelf Science 82: 193-200 [https://doi.org/10.1016/j.ecss.2008.12.010]

Nagelkerken I, Van der Velde (2004) Relative importance of interlinked mangroves and seagrass beds as feeding habitats for juvenile reef fish on a Caribbean island. Marine Ecology Progress Series 274: 153-159 [https://doi.org/10.3354/meps274153]

Nagelkerken I, Blaber SJM, Bouillon S, Green P, Haywood M, Kirton LG, Meynecke JO, Pawlik J, Penrose HM, Sasekumar A, Somerfield PJ (2008) The habitat function of mangroves for terrestrial and marine fauna: A review. Aquatic Botany 89: 155-185 [https://doi.org/10.1016/j.aquabot.2007.12.007]

Nagelkerken I (2009) Evaluation of nursery function of mangroves and seagrass beds for tropical decapods and reef fishes: Patterns and underlying mechanisms. In: Nagelkerken I (ed) Ecological connectivity among tropical coastal ecosystems. Springer, Dordrecht, Netherlands. pp 357-399 [https://doi.org/10.1007/978-90-481-2406-0_10]

Nakamura Y, Horinouchi M, Shibuno T, Tanaka Y, Miyajima T, Koike I, Kurokura H, Sano M (2008) Evidence of ontogenetic migration from mangroves to coral reefs by black-tail snapper *Lutjanus fulvus*: stable isotope approach. Marine Ecology Progress Series 355: 257-266 [https://doi.org/10.3354/meps07234]

NBS (2013) Population and housing census: Population distribution by administrative areas. Dar es Salaam, Tanzania: Ministry of Finance, Government of Tanzania

Oczkowski A, Markham E, Hanson A, Wigand C (2014) Carbon stable isotopes as indicators of coastal eutrophication. Ecological Applications 24: 457-466 [https://doi.org/10.1890/13-0365.1]

Oczkowski A, Santos E, Gray A, Miller K, Huertas E, Hanson A, Martin A, Watson EB, Wigand C (2020) Tracking the dynamic ecological history of a tropical urban estuary as it responds to human pressures. Ecosystems 23: 231-245 [https://doi.org/10.1007/s10021-019-00399-1]

Parsons T, Maita Y, Lalli CM (1984) Amanual of chemical and biological methods for seawater analysis. Biological Oceanographic Processes. Pergamon Press, New York. 173 pp

Pinnegar JK, Polunin NVC (1999) Differential fractionation of δ13C and δ15N among fish tissues: implications for the study of trophic interactions. Functional Ecology 13: 225-231 [https://doi.org/10.1046/j.1365-2435.1999.00301.x]

R Core Team R (2020) A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria [https://www.R-project.org/]

Samper-Villarreal J, Cortés J, Polunin NVC (2018). Isotopic evidence of subtle nutrient enrichment in mangrove habitats of Golfo Dulce, Costa Rica. Hydrological Processes 32: 1956-1964 [https://doi.org/10.1002/hyp.13133]

Sanderson BL, Tran CD, Coe HJ, Pelekis V, Steel EA, Reichert WL (2009) Nonlethal sampling of fish caudal fins yields valuable stable isotope data for threatened and endangered fishes. Transactions of the American Fisheries Society 138: 1166-1177 [https://doi.org/10.1577/T08-086.1]

Savage C (2005) Tracing the influence of sewage nitrogen in a coastal ecosystem using stable nitrogen isotopes. Ambio: A Journal of the Human Environment 34: 145-150 [https://doi.org/10.1579/0044-7447-34.2.145]

Selkoe KA, Blenckner T, Caldwell MR, Crowder LB, Erickson AL, Essington TE, Estes JA, Fujita RM, Halpern BS, Hunsicker ME, Kappel CV, Kelly RP, Kittinger JN, Levin PS, Lynham JM, Mach ME, Martone RG, Mease LA, Salomon AK, Samhouri JF, Scarborough C, Stier AC, White C, Zedler J (2015) Principles for managing marine ecosystems prone to tipping points. Ecosystem Health and Sustainability 1: 1-18 [https://doi.org/10.1890/ehs14-0024.1]

Serrao-Neumann S, Davidson JL, Baldwin CL, Dedekorkut-Howes A, Ellison JC, Holbrook NJ, Howes M, Jacobson CJ, Morgan EA (2016) Marine governance to avoid tipping points: Can we adapt the adaptability envelope? Marine Policy 2016 65: 56-67 [https://doi.org/10.1016/j.marpol.2015.12.007]

Staehr PA, Testa J, Carstensen J (2017) Decadal changes in water quality and net productivity of a shallow Danish estuary following significant nutrient reductions. Estuaries and Coasts 40: 63-79 [https://doi.org/10.1007/s12237-016-0117-x]

Staehr PA, Sheikh M, Rashid R, Ussi A, Suleiman M, Kloiber U, Dahl K, Tairova Z, Strand J (2018) Managing human pressures to restore ecosystem health of Zanzibar coastal waters. Journal of Aquaculture & Marine Biology 7: 59-70 [https://doi.org/10.15406/jamb.2018.07.00185]

Teichberg M, Fox SE, Olsen YS, Valiela I, Martinetto P, Iribarne O, Muto EY, Petti MAV, Corbisier TN, Soto-Jimenez M, Osuna FP, Catro P, Freitas H, Zitelli A, Cardinaletti M, Tagliapietra D (2010) Eutrophication and macroalgal blooms in temperate and tropical coastal waters: nutrient enrichment experiments with *Ulva* spp. Global Change Biology 16: 2624-2637 [https://doi.org/10.1111/j.1365-2486.2009.02108.x]

Tronquart NH, Mazeas L, Reuilly-Manenti L, Zahm A, Belliard J (2012) Fish fins as non-lethal surrogates for muscle tissues in freshwater food web studies using stable isotopes. Rapid Communications in Mass Spectrometry 26: 1603-1608 [https://doi.org/10.1002/rcm.6265]

Valladares S, Planas M (2012) Non-lethal dorsal fin sampling for stable isotope analysis in seahorses. Aquatic Ecology 46: 363-370 [https://doi.org/10.1007/s10452-012-9407-y]

Vikas M, Dwarakish GS (2015) Coastal pollution: A review. Aquatic Procedia 4: 381-388 [https://doi.org/10.1016/j.aqpro.2015.02.051]

Watson SCL, Grandfield FGC, Herbert RJH, Newton AC (2018) Detecting ecological thresholds and tipping points in the natural capital assets of a protected coastal ecosystem. Estuarine, Coastal and Shelf Science 215: sell12-123 [https://doi.org/10.1016/j.ecss.2018.10.006]

Xiao X, Agusti S, Lin F, Li K, Pan Y, Yu Y, Zheng Y, Wu J, Duarte CM (2017) Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. Scientific Reports 7: 46613 [https://doi.org/10.1038/srep46613]

Yuen KK (1974) The two-sample trimmed t for unequal population variances. Biometrika 61: 165-170 [https://doi.org/10.1093/biomet/61.1.165]