




Regional Variation in the Trophic Ecology of Wahoo (*Acanthocybium solandri*) in the Western Atlantic Ocean

Brendan Gough ¹, Alexandra Prouse ^{1,*}, Michael A. Dance ², R. J. David Wells ^{1,3} and Jay R. Rooker ^{1,3}

¹ Department of Marine Biology, Texas A&M University at Galveston, Galveston, TX 77553, USA; bgough526@gmail.com (B.G.); wellsr@tamug.edu (R.J.D.W.); rookerj@tamug.edu (J.R.R.)

² Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA; mdance1@lsu.edu

³ Department of Ecology and Conservation Biology, Texas A&M University, College Station, TX 77843, USA

* Correspondence: alexandrayard@tamu.edu

Abstract: Intrinsic tracers, such as stable isotopes of carbon and nitrogen, are common dietary markers that accumulate in the muscle tissue of consumers and can be used to determine the dietary sources and trophic positions of consumers. The aim of this study was to assess regional variation in the trophic ecology of wahoo (*Acanthocybium solandri*) using bulk stable isotopes. Muscle biopsies of wahoo were collected from four regions in the western Atlantic Ocean: the eastern Gulf of Mexico, western Gulf of Mexico, Northwest Atlantic Ocean, and Caribbean Sea. Muscle tissue $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for wahoo ranged from -15.8‰ to -18.8‰ and from 7.2‰ to 12.8‰ , respectively. Wahoo collected in the Caribbean Sea displayed the highest mean $\delta^{13}\text{C}$ value (-16.3‰), and individuals from this region were statistically different from the three other regions sampled. Mean $\delta^{15}\text{N}$ values were elevated for wahoo collected in the eastern and western Gulf of Mexico (11.4‰ and 11.1‰ , respectively), and the values were over 2‰ higher than samples from the Northwest Atlantic Ocean and Caribbean Sea. Trophic position (TP) was estimated using $\delta^{15}\text{N}$ baselines (zooplankton) and $\delta^{15}\text{N}$ wahoo values for each region, and mean TP was 0.4 to 0.9 higher in the Caribbean Sea relative to the three other regions, suggesting that wahoo in this region feed on higher-trophic-level prey. The results indicate that $\delta^{15}\text{N}$ baselines and the trophic positions of wahoo each vary as a function of their geographic location, which supports the hypothesis that this species feeds opportunistically throughout its range.

Keywords: trophic ecology; dietary tracers; stable isotope analysis; trophic position

Key Contribution: This study demonstrates regional variation in the intrinsic dietary tracers of wahoo throughout four regions of their range, showcasing the importance of $\delta^{15}\text{N}$ baselines in estimating the trophic position of migratory predators.



Citation: Gough, B.; Prouse, A.; Dance, M.A.; Wells, R.J.D.; Rooker, J.R. Regional Variation in the Trophic Ecology of Wahoo (*Acanthocybium solandri*) in the Western Atlantic Ocean. *Fishes* **2023**, *8*, 519. <https://doi.org/10.3390/fishes8100519>

Academic Editors: S.S.S. Sarma and Felipe Galván-Magaña

Received: 10 August 2023

Revised: 9 October 2023

Accepted: 18 October 2023

Published: 20 October 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Top predators play an important role in the overall health and sustainability of marine ecosystems. Many higher-order predators (e.g., billfishes, swordfish, tunas, wahoo) are capable of regulating populations of lower-level consumers through top-down control [1]. As a result, shifts in their foraging may initiate trophic cascades that affect multiple trophic levels of the food web [1]. Given the importance of top-down regulation on ecosystem productivity and resiliency, scientists are increasingly interested in determining the trophic relationships of higher-order consumers within their respective food webs, which can provide valuable information on the role of these predators in regulating energy transfer and community structure within marine food webs.

An improved understanding of the source(s) of organic matter (i.e., primary producers) supporting top predators and the trophic structure of marine food webs is crucial for

resource managers, as it influences the stability and resiliency of marine ecosystems. To date, trophic information for many predatory marine teleosts is limited, and understanding the role of these apex predators in marine ecosystems throughout their range is vital for proper management of those systems. Intrinsic dietary tracers, such as stable isotopes, are increasingly used in trophic ecology studies of marine fishes [2–5]. Stable isotope ratios of carbon and nitrogen can elucidate source(s) of organic matter that supports a community and the trophic position of consumers in the food web, respectively. $\delta^{13}\text{C}$ only fractionates 0.5–1.5‰ per trophic level, and this marker is typically used to determine the source(s) of organic matter supporting consumers [5]. In contrast, $\delta^{15}\text{N}$ is often used as a proxy for trophic position because this marker fractionates approximately 3‰ over each trophic level [5].

Wahoo (*Acanthocybium solandri*) are members of the family Scombridae that includes tunas and mackerels. Wahoo are predators found in the epipelagic zone throughout tropical and subtropical waters around the globe [6]. Wahoo are assumed to be opportunistic piscivores with occasional contributions to diet composition from other taxa, including cephalopods and crustaceans [7,8]. The aim of this study was to apply stable isotope analysis (SIA) to evaluate the source(s) of organic matter supporting wahoo and their trophic position across four geographic regions in the western Atlantic Ocean. Two common dietary markers ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) were used to elucidate broad feeding inferences of wahoo and assess regional variation in trophic relationships.

2. Materials and Methods

Muscle biopsies of wahoo were collected from four sampling regions in June through October of 2021 (Figure 1): the eastern Gulf of Mexico ($n = 11$), western Gulf of Mexico ($n = 10$), Northwest Atlantic Ocean ($n = 10$), and Caribbean Sea ($n = 10$). Biopsies were opportunistically collected from individuals caught via recreational and commercial fishing operations once vessels returned to port. All sampled individuals were between 110 cm and 140 cm fork length [9], representing sexually mature adults [10]. Muscle biopsies were collected in the field and stored at $-20\text{ }^{\circ}\text{C}$ between collection and processing. Cleaned samples were then lyophilized for 24 h; freezing was completed at $-45\text{ }^{\circ}\text{C}$ for 12 h, and drying was completed via vacuum pump at $50\text{ }^{\circ}\text{C}$ for another 12 h. Lyophilized samples were powdered with a mortar and pestle and weighed to $1\text{ mg} \pm 0.1\text{ mg}$ in $9 \times 5\text{ mm}$ tin capsules. Tissue samples were analyzed on an elemental analyzer isotope ratio mass spectrometer (EA-IRMS; Sercon Ltd., Cheshire, UK) at the University of California Davis Stable Isotope Facility. Delta notation (δ) was used to present isotope ratios ($^{13}\text{C}:^{12}\text{C}$ or $^{15}\text{N}:^{14}\text{N}$) relative to international standards: Vienna Pee Dee Belemnite (VPDB) for carbon and air (N_2) for nitrogen. The long-term standard deviations of the isotope ratios at this facility are 0.2‰ for $\delta^{13}\text{C}$ and 0.3‰ for $\delta^{15}\text{N}$. C:N ratios of the analyzed samples were below 3.5, indicating that $\delta^{13}\text{C}$ values were not significantly influenced by lipid content in the muscle and thus did not require lipid extraction [11]. Although smaller sample sizes may affect the power of statistical tests, variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures within regions was lower than among regions and thus the sample size was sufficient to assess regional differences.

Trophic position (TP) was calculated using Equation (1), where 3 represents the average enrichment of $\delta^{15}\text{N}$ per trophic level [12]. Because baseline $\delta^{15}\text{N}$ values of the primary producers varies across sampled regions, adjusted TP (TP_{Adj}) estimates were estimated using regional $\delta^{15}\text{N}$ values reported for the broader Atlantic Ocean and Gulf of Mexico [13,14]; standard TP (TP_{STD}) estimates based on a single $\delta^{15}\text{N}$ baseline value that does not account for regional variation were also estimated. The isoscapes used provided $\delta^{15}\text{N}$ values for zooplankton ($\delta^{15}\text{N}_{\text{ZP}}$), which are indicative of the trophic level above primary producers. Following the average enrichment of $\delta^{15}\text{N}$ per trophic level stated above, the $\delta^{15}\text{N}_{\text{producer}}$ value was determined by $(\delta^{15}\text{N}_{\text{ZP}} - 3)$.

$$\text{TP}_{\text{consumer}} = 1 + (\delta^{15}\text{N}_{\text{consumer}} - \delta^{15}\text{N}_{\text{producer}})/3 \quad (1)$$

Regional variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values were investigated with a one-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD) test. Quadratic discriminant function analysis was used to determine classification success for each collection region based on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. All statistical analysis was conducted in RStudio (R version 4.2.2).

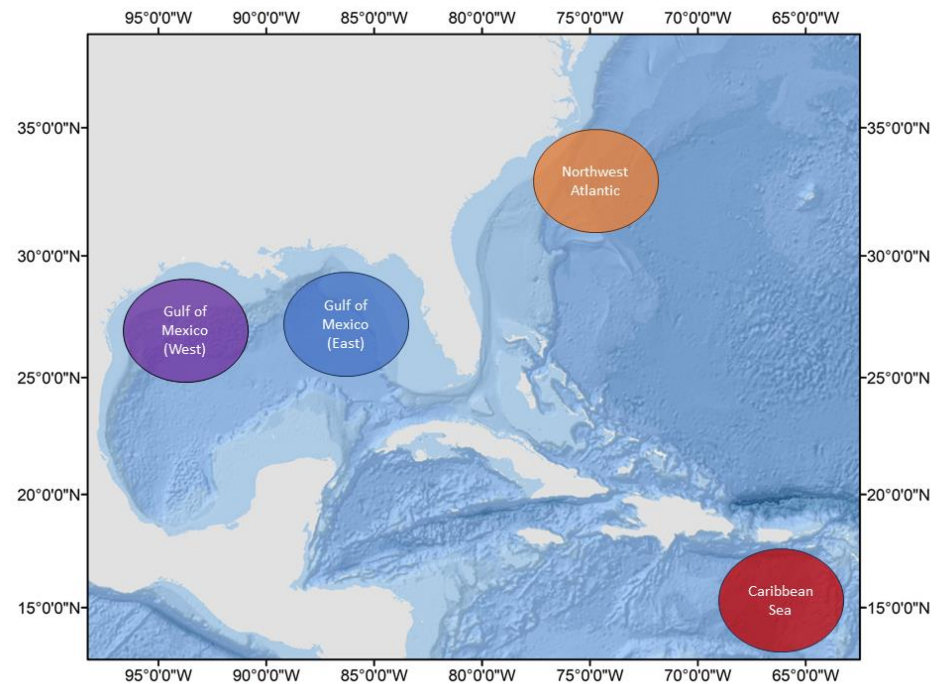


Figure 1. Sampling regions for wahoo in the western Atlantic Ocean: western Gulf of Mexico (Texas), eastern Gulf of Mexico (Mississippi to Florida), Caribbean Sea (Puerto Rico, U.S. Virgin Islands), and Northwest Atlantic Ocean (North Carolina). All samples were opportunistically collected via recreational and commercial fishing operations once vessels returned to port.

3. Results

3.1. Regional $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ Values

Muscle tissue $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wahoo varied across the four geographic locations sampled. Specifically, $\delta^{13}\text{C}$ values of wahoo from the Caribbean Sea were significantly different compared to the Northwest Atlantic Ocean and both regions in the Gulf of Mexico (ANOVA, $p < 0.01$; Figure 2). Wahoo collected from the Caribbean Sea had significantly enriched $\delta^{13}\text{C}$ values ($-16.3\text{‰} \pm 0.32$; mean ± 1 SD), with relatively similar signatures shown in the other three regions: Northwest Atlantic Ocean (-17.2 ± 0.66), eastern Gulf of Mexico (-17.1 ± 0.26), western Gulf of Mexico (-17.0 ± 0.29) (Table 1). Regional variation was also observed for muscle tissue $\delta^{15}\text{N}$ values, with samples collected from both regions in the Gulf of Mexico (east = 11.4 ± 1.0 , west = 11.1 ± 1.1) displaying significantly higher values relative to samples from the Northwest Atlantic Ocean (9.2 ± 0.59) and Caribbean Sea (8.4 ± 0.53) (ANOVA, $p < 0.01$; Figure 2); however, no significant differences were detected between the two regions in the Gulf of Mexico or between the two regions in the Atlantic Ocean.

Collection locations in the Gulf of Mexico and Atlantic Ocean were grouped to further evaluate large-scale variation, and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures from the two larger geographic regions were significantly different (MANOVA, $p < 0.01$). Quadratic discriminant function analysis (QDFA) parameterized with $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures displayed a relatively high cross-validated classification success (85%) in the two larger regions, indicating that these dietary signatures show promise for retrospectively determining the collection location of wahoo (Gulf of Mexico vs. Atlantic Ocean) for samples of unknown origin.

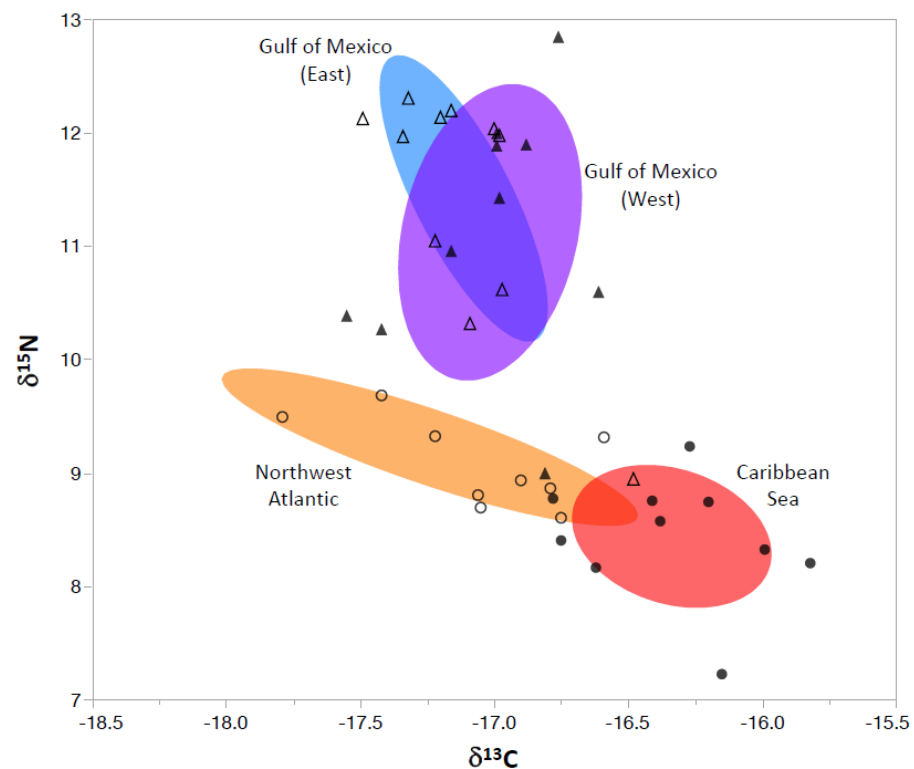


Figure 2. Confidence ellipses (50%) based on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of wahoo from the Gulf of Mexico (East, open triangles; West, filled triangles), Northwest Atlantic Ocean (open circles), and Caribbean Sea (filled circles). Values for individual wahoo shown with symbols.

Table 1. Size (mean FL in cm \pm 1 SD), baseline zooplankton $\delta^{15}\text{N}$ ($\delta^{15}\text{N}_{\text{ZP}}$) values [13,14], standard (STD) trophic position (based on same $\delta^{15}\text{N}$ baseline value for all regions), and adjusted (ADJ) range and mean estimates of trophic position (mean \pm standard deviation) for wahoo using region-specific $\delta^{15}\text{N}_{\text{ZP}}$ values from the four sampling regions. TP_{STD} based on standard $\delta^{15}\text{N}_{\text{ZP}}$ of 6.2 for all four regions, while TP_{ADJ} range and mean estimates based on region-specific $\delta^{15}\text{N}_{\text{ZP}}$ values shown in table.

Region	Size (cm FL)	$\delta^{15}\text{N}_{\text{ZP}}$	TP_{STD}	TP_{ADJ} Range	TP_{ADJ} Mean
Gulf of Mexico					
East	130.1 \pm 8.0	6.2	3.7 \pm 0.4	2.9–4.0	3.7 \pm 0.4
West	124.4 \pm 10.1	6.2	3.6 \pm 0.4	2.9–4.2	3.6 \pm 0.4
Atlantic Ocean					
Caribbean Sea	132.3 \pm 6.8	2.0	2.7 \pm 0.2	3.7–4.4	4.1 \pm 0.2
Northwest Atlantic	123.9 \pm 5.1	5.5	3.0 \pm 0.2	3.0–3.7	3.2 \pm 0.2

3.2. Regional TP Estimates

Estimates of standard trophic position (TP_{STD}) for wahoo were estimated using a standard baseline for all regions. In addition, adjusted TP (TP_{ADJ}) estimates were derived using $\delta^{15}\text{N}_{\text{ZP}}$ values (baseline) for each region from available isoscapes [13,14]. Standard TP estimates of wahoo were between 2.7 and 3.7, with significantly higher values reported for wahoo collected in the Gulf of Mexico (ANOVA, $p < 0.001$). Adjusted TP estimates of wahoo derived using regional estimates of $\delta^{15}\text{N}_{\text{ZP}}$ markedly increased the position of individuals from the Caribbean Sea by nearly two trophic steps (4.1). While this region was characterized by the lowest TP using a single $\delta^{15}\text{N}$ baseline value, TP was approximately a half to full trophic step higher when using region-specific baseline values and significantly different from the three other regions (Tukey HSD, $p < 0.05$). Adjusted TP estimates using

region-specific baselines were lowest in the Northwest Atlantic Ocean, and both TP range and means were similar (3.6–3.7) between the two regions in the Gulf of Mexico.

4. Discussion

Regional differences in muscle tissue $\delta^{13}\text{C}$ values of wahoo collected across the four regions were observed, but similarities were also present for individuals collected from different regions within the Gulf of Mexico and within the Atlantic Ocean. Similar $\delta^{13}\text{C}$ values for wahoo in both the eastern and western Gulf of Mexico support the premise that source(s) of organic matter supporting the pelagic food web and associated top predators in this region are similar in ecosystems both east and west of the Mississippi River Delta. Recently reported $\delta^{13}\text{C}$ isoscapes for zooplankton in the outer shelf and slope waters of the northern Gulf of Mexico also reported limited variation in $\delta^{13}\text{C}$ values [15], which is in accord with our findings for wahoo. Outside the Gulf of Mexico, our finding of comparable $\delta^{13}\text{C}$ values for wahoo collected in the Northwest Atlantic Ocean and Caribbean Sea was less expected given the distance between the two regions and different latitudinal biomes of each collection area (tropical versus temperate); however, variation in the $\delta^{13}\text{C}$ values of both phytoplankton and zooplankton in the general areas that wahoo were sampled in the Northwest Atlantic Ocean (Mid-Atlantic Bight) and Caribbean Sea (Lesser Antilles) is generally limited (~1–2‰ range) [16]. This indicates that although these two provinces are separated geographically, primary sources of organic matter and/or $\delta^{13}\text{C}$ values of major autotrophs in both regions may be comparable.

Muscle tissue $\delta^{15}\text{N}$ values of wahoo also varied across the four regions, with similarities observed for individuals collected from the two regions in the Gulf of Mexico and from the two regions in the Atlantic Ocean. $\delta^{15}\text{N}$ values for wahoo from the Gulf of Mexico were significantly higher than individuals from the Atlantic Ocean and generally comparable to previously reported values for wahoo throughout their range [9,17]. A study conducted in the Galapagos Islands reported mean $\delta^{15}\text{N}$ values for wahoo of 15.3‰, nearly 4.0‰ higher than any region assessed in the present study [18]; however, estimating adjusted TP using mean zooplankton $\delta^{15}\text{N}$ values from this region of the Pacific Ocean resulted in similar values in our study [19], further confirming the importance of incorporating region-specific baseline $\delta^{15}\text{N}$ data for estimating TP. Unique baseline $\delta^{15}\text{N}$ values were present across the sampling locations of this study, with significantly lower $\delta^{15}\text{N}$ values of zooplankton ($\delta^{15}\text{N}_{\text{ZP}}$) present in the Caribbean Sea [20] compared to the Gulf of Mexico and Northwest Atlantic Ocean. Lower $\delta^{15}\text{N}_{\text{ZP}}$ values were shown to be characteristic of oligotrophic waters due to increased nitrogen fixation by diazotrophic cyanobacteria [20,21], whereas waters influenced by anthropogenic nitrogen sources from riverine output such as the Mississippi River delta tend to report higher $\delta^{15}\text{N}_{\text{ZP}}$ values [14,22]. Despite significantly higher $\delta^{15}\text{N}$ values for wahoo in the Gulf of Mexico, incorporating $\delta^{15}\text{N}_{\text{ZP}}$ values into TP estimates accounted for regional variation in $\delta^{15}\text{N}$ baselines and elevated the TP of wahoo from the Caribbean Sea. Nevertheless, adjusted TP estimates of wahoo from all four regions were comparable to previously reported values in different parts of their range and also similar to other higher-order marine teleosts in pelagic ecosystems [10,23–25], further supporting the premise that wahoo appear to be opportunistic predators that feed at similar trophic levels throughout their range in tropical and subtropical waters.

It is well understood that baseline $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values and prey fields vary spatially and temporally, and therefore movements or migrations of predators can lead to shifts in prey selection and TP. As a result, a better understanding of the home range and migrations of wahoo may help explain observed regional trends observed in muscle tissue $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. For example, similarities in muscle tissue $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for wahoo in both the eastern and western Gulf of Mexico may be associated with active movements or migrations between the two regions. Conversely, conspicuous differences in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values observed for individuals collected from the two larger geographic (Gulf of Mexico vs. Atlantic Ocean) regions may indicate that long-distance movements between these two regions is less likely. Data on the population connectivity of wahoo coupled with

higher quality $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ baselines, including other sources of dietary information, are critically needed to elucidate the drivers of region-specific variation and further clarify trophic relationships for this species.

Author Contributions: Conceptualization, J.R.R. and R.J.D.W.; methodology, J.R.R. and R.J.D.W.; formal analysis, B.G., A.P. and J.R.R.; writing—original draft preparation, B.G., A.P. and J.R.R.; writing—review and editing, B.G., A.P., J.R.R., R.J.D.W. and M.A.D.; visualization, A.P. and J.R.R.; supervision, J.R.R.; funding acquisition, J.R.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported with funding from the Gulf Research Institute for Highly Migratory Species and the Research and Graduate Studies Office at Texas A&M University at Galveston.

Institutional Review Board Statement: All collections were performed in accordance with relevant guidelines and regulations of institutional animal care and use committees (IACUC) at Texas A&M University. No official animal use license was required because biological sampling was performed on harvested (non-living) specimens from commercial and recreational fishing operations.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated for this study can be made available upon request to the corresponding author.

Acknowledgments: This project was carried out in support and mentorship of one undergraduate student (B.G.) participating in the Undergraduate Research Scholars program at Texas A&M University at Galveston. The authors would like to thank collaborators at Texas A&M University at Galveston, Louisiana State University, North Carolina State University, and PezMar Research L.L.C. for their assistance in sample collection and members of the Fisheries Ecology Lab and Shark Biology and Fisheries Science Lab at Texas A&M University at Galveston for their support.

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

References

1. Shears, N.T.; Babcock, R.C. Marine reserves demonstrate top-down control of community structure on temperate reefs. *Oecologia* **2002**, *132*, 131–142. [[CrossRef](#)] [[PubMed](#)]
2. Chang, Y.-C.; Chiang, W.-C.; Madigan, D.J.; Tsai, F.-Y.; Chiang, C.-L.; Hsu, H.-H.; Lin, S.-M.; Zhuang, M.-Y.; Sun, C.-T.; Chen, L.-C. Trophic dynamics and feeding ecology of skipjack tuna (*Katsuwonus pelamis*) off Eastern and Western Taiwan. *Molecules* **2022**, *27*, 1073. [[CrossRef](#)] [[PubMed](#)]
3. Richards, T.M.; Sutton, T.T.; Wells, R.D. Trophic structure and sources of variation influencing the stable isotope signatures of meso- and bathypelagic micronekton fishes. *Front. Mar. Sci.* **2020**, *7*, 507992. [[CrossRef](#)]
4. Speed, C.; Meekan, M.; Field, I.; McMahon, C.; Abrantes, K.; Bradshaw, C. Trophic ecology of reef sharks determined using stable isotopes and telemetry. *Coral Reefs* **2012**, *31*, 357–367. [[CrossRef](#)]
5. Wells, R.D.; Cowan Jr, J.H.; Fry, B. Feeding ecology of red snapper *Lutjanus campechanus* in the northern Gulf of Mexico. *Mar. Ecol. Prog. Ser.* **2008**, *361*, 213–225. [[CrossRef](#)]
6. Sepulveda, C.A.; Aalbers, S.A.; Ortega-Garcia, S.; Wegner, N.C.; Bernal, D. Depth distribution and temperature preferences of wahoo (*Acanthocybium solandri*) off Baja California Sur, Mexico. *Mar. Biol.* **2011**, *158*, 917–926. [[CrossRef](#)]
7. Mendoza-Avila, M.; Zavala-Zambrano, G.; Galván-Magaña, F.; Loo-Andrade, P. Feeding habits of wahoo (*Acanthocybium solandri*) in the eastern Pacific Ocean. *J. Mar. Biol. Assoc. United Kingd.* **2017**, *97*, 1505–1510. [[CrossRef](#)]
8. Gao, C.; Tian, S.; Kindong, R.; Dai, X. Biology and environmental preferences of wahoo, *Acanthocybium solandri* (Cuvier, 1832), in the Western and Central Pacific Ocean (WCPO). *J. Mar. Sci. Eng.* **2020**, *8*, 184. [[CrossRef](#)]
9. Martins, K.; Pelage, L.; Justino, A.K.; Frédou, F.L.; Júnior, T.V.; Le Loc’h, F.; Travassos, P. Assessing trophic interactions between pelagic predatory fish by gut content and stable isotopes analysis around Fernando de Noronha Archipelago (Brazil), Equatorial West Atlantic. *J. Fish Biol.* **2021**, *99*, 1576–1590. [[CrossRef](#)] [[PubMed](#)]
10. Oxenford, H.A.; Murray, P.A.; Luckhurst, B.E. The biology of wahoo (*Acanthocybium solandri*) in the western central Atlantic. *Gulf Caribb. Res.* **2003**, *15*, 33–49. [[CrossRef](#)]
11. Post, D.M.; Layman, C.A.; Arrington, D.A.; Takimoto, G.; Quattrochi, J.; Montana, C.G. Getting to the fat of the matter: Models, methods and assumptions for dealing with lipids in stable isotope analyses. *Oecologia* **2007**, *152*, 179–189. [[CrossRef](#)] [[PubMed](#)]
12. Vander Zanden, J.M.; Rasmussen, J.B. Variation in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ trophic fractionation: Implications for aquatic food web studies. *Limnol. Oceanogr.* **2001**, *46*, 2061–2066. [[CrossRef](#)]

13. Graham, B.S.; Koch, P.L.; Newsome, S.D.; McMahon, K.W.; Aurioles, D. Using isoscapes to trace the movements and foraging behavior of top predators in oceanic ecosystems. In *Isoscapes: Understanding Movement, Pattern, and Process on Earth through Isotope Mapping*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 299–318.
14. McMahon, K.W.; Hamady, L.L.; Thorrold, S.R. A review of ecogeochemistry approaches to estimating movements of marine animals. *Limnol. Oceanogr.* **2013**, *58*, 697–714. [[CrossRef](#)]
15. Hernández-Sánchez, O.G.; Camacho-Ibar, V.F.; Barbero, L.; Herguera, J.C.; Herzka, S.Z. A gulf-wide synoptic isoscape of zooplankton isotope ratios reveals the importance of nitrogen fixation in supporting secondary production in the central Gulf of Mexico. *Front. Mar. Sci.* **2023**, *9*, 1025387. [[CrossRef](#)]
16. Magozzi, S.; Yool, A.; Vander Zanden, H.; Wunder, M.; Trueman, C. Using ocean models to predict spatial and temporal variation in marine carbon isotopes. *Ecosphere* **2017**, *8*, e01763. [[CrossRef](#)]
17. Rooker, J.R.; Turner, J.P.; Holt, S.A. Trophic ecology of Sargassum-associated fishes in the Gulf of Mexico determined from stable isotopes and fatty acids. *Mar. Ecol. Prog. Ser.* **2006**, *313*, 249–259. [[CrossRef](#)]
18. Páez-Rosas, D.; Galván-Magaña, F.; Baque-Menoscal, J.; Tripp-Valdez, A.; Fischer, C.; Hearn, A. Trophic preferences of three pelagic fish inhabiting the Galapagos Marine Reserve: Ecological inferences using multiple analyses. *Environ. Biol. Fishes* **2020**, *103*, 647–665. [[CrossRef](#)]
19. Páez-Rosas, D.; Aurioles-Gamboa, D.; Alava, J.J.; Palacios, D.M. Stable isotopes indicate differing foraging strategies in two sympatric otariids of the Galapagos Islands. *J. Exp. Mar. Biol. Ecol.* **2012**, *424*, 44–52. [[CrossRef](#)]
20. Dorado, S.; Rooker, J.R.; Wissel, B.; Quigg, A. Isotope baseline shifts in pelagic food webs of the Gulf of Mexico. *Mar. Ecol. Prog. Ser.* **2012**, *464*, 37–49. [[CrossRef](#)]
21. Montoya, J.P.; Carpenter, E.J.; Capone, D.G. Nitrogen fixation and nitrogen isotope abundances in zooplankton of the oligotrophic North Atlantic. *Limnol. Oceanogr.* **2002**, *47*, 1617–1628. [[CrossRef](#)]
22. Saino, T.; Hattori, A. ^{15}N natural abundance in oceanic suspended particulate matter. *Nature* **1980**, *283*, 752–754. [[CrossRef](#)]
23. Cai, Y.; Rooker, J.R.; Gill, G. Bioaccumulation of Mercury in Pelagic Fishes from the NW Gulf of Mexico and Its Relationship with Length, Location, Collection Year, and Trophic Level. 2006. Available online: <http://hdl.handle.net/1834/29782> (accessed on 12 July 2023).
24. Franks, J.S.; Hoffmayer, E.R.; Ballard, J.R.; Garber, N.M.; Garber, A.F. Diet of wahoo, *Acanthocybium solandri*, from the Northcentral Gulf of Mexico. *Proc. 60th Gulf Caribb. Fish. Inst.* **2007**, *60*, 353–362.
25. Manooch III, C.S.; Hogarth, W.T. Stomach contents and giant trematodes from wahoo, *Acanthocybium solandri*, collected along the South Atlantic and Gulf coasts of the United States. *Bull. Mar. Sci.* **1983**, *33*, 227–238.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.