Otolith $\delta^{18}O$ as a tracer of yellowfin tuna (*Thunnus albacares*) nursery origin in the Indian Ocean

Iraide Artetxe-Arrate*[1], Igaratza Fraile[1], Jessica Farley[2], Naomi Clear[2], Audrey M. Darnaude[3], David L. Dettman[4], Paige Eveson[2], Iñigo Krug[1], Natacha Nikolic[3#], Anais Médieu[3], Mohamed Ahusan[5], Matt Landsdell[2], Craig Proctor[2], Asep Priatna[6], Pratiwi Lestari[6], Muhammad Taufik[6], Denham Parker[7], Hamid Badar Usmani[8], Kashifa Zehra[8], Mohammad Wasim Khan[8], Umair Shahid[9], Syed Meesum Reza Kazmi[9], Saeed ul Islam[9], Mariam Tariq[9], Sidra Zafar[9], Jaweria Zaidi[9], Campbell Davies[2], Francis Marsac[10] and Hilario Murua[11]

[1] AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Herrera Kaia, Portualdea z/g, 20110 Pasaia – Gipuzkoa, Spain

[2] CSIRO Oceans and Atmosphere, Castray Esplanade, Hobart, Tasmania, Australia

[3] Marbec, Univ Montpellier, CNRS, Ifremer, IRD, Montpellier, France

[4] Environmental Isotope Laboratory, Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA

[5] Maldives Marine Research Institute, Moonlight Hingun, Male, Maldives

[6] Research Institute for Marine Fisheries,RIMF, Indonesia

[7] Department of Agriculture, Forestry and Fisheries, South Africa, and Stewart Norman, CAPFISH, South Africa

[8] Marine Fisheries Department, Government of Pakistan

[9] WWF Pakistan, Karachi, Pakistan

[10] Marbec, Univ Montpellier, CNRS, Ifremer, IRD, Sète, France

[11] International Seafood Sustainability Foundation, 1440 G Street NW, Washington, DC 20005, USA.

[#] Present address: INRAE, Saint-Pée-sur-Nivelle, France

*Corresponding author e-mail address: i.artetxe73@gmail.com

Abstract

Oxygen stable isotope in otoliths ($\delta^{18}O$) was used to investigate stock structure of yellowfin tuna (*Thunnus albacares*) across the Indian Ocean. Differences in otolith $\delta^{18}O$ signatures among young of the year (YOY) yellowfin tuna were examined to determine whether there was sufficient distinction among three main nursery areas of the equatorial Indian Ocean (West, Central and East), to establish a reference isotopic signature (a baseline). The nursery origin of juvenile yellowfin (47-75 cm fork length (FL)) tuna from Reunion and Pakistan was then compared with these nursery signals. Juvenile fish from Reunion show $\delta^{18}O$ signatures comparable with those of

the nearest nursery area (West nursery), but juvenile fish from the Pakistan show distinctive $\delta^{18}O$ composition compared to any of the nursery areas described. Therefore, samples from Pakistan were considered as an additional baseline signature for adult assignment purposes. Quadratic discriminant function analysis was used to assign adult individuals to one of the four areas in our baseline. Results indicate that western nursery was contributing the most to the fish analysed (24 adult out of 39 were predicted to this nursery) with a minor contribution from Pakistan (5 individuals). No Central or East nursery origins were detected among the adult sample. A fraction of yellowfin tuna (11 individuals) was left unclassified. This is an important first step towards understanding the mixing rates and the connectivity of yellowfin tuna in the Indian Ocean.

1. Introduction

Yellowfin tuna (*Thunnus albacares*) inhabit the pelagic ecosystem of the tropical and subtropical regions of the Atlantic, Indian and Pacific Oceans (Collette and Nauen, 1983). Yellowfin tuna has been subject to high fishing pressure over the last three decades (ISSF, 2020), particularly in the Indian Ocean. Here, recent increases in catches has led to estimates of fishing mortality rates exceeding the Maximum Sustainable Yield (MSY) (IOTC, 2019; ISSF, 2020). The Indian Ocean yellowfin tuna stock is, therefore, considered overfished and subject to overfishing (IOTC, 2018). The Indian Ocean Tuna Commission (IOTC) assessment assumes that yellowfin tuna constitutes a single stock in the Indian Ocean due to the rapid and large-scale movements provided by the Indian Ocean Regional Tuna Tagging Program (RTTP-IO) (IOTC, 2017), although some regional studies suggest that the stock structure and spatial dynamics could be more complex (Dammannagoda et al., 2008; Kunal et al., 2013; Moore et al., 2019).

Yellowfin tuna can be found throughout the Indian Ocean, as far south as 45ºS (Sharp, 2001), but their spawning activity is restricted to environments where surface water temperature exceeds 24ºC (Schaefer, 2001). The main spawning grounds in the Indian Ocean have been described along the equatorial region (Nootmorn et al., 2005; Zhu et al., 2008; Zudaire et al., 2013). As adults, yellowfin tuna show extensive migrations between spawning areas in this equatorial

waters and feeding grounds in southern and northern latitudes (Fonteneau and Pallares-Soubrier, 1995). However, the relative importance of different spawning areas to the total catches, and the degree of connectivity and mixing rates of yellowfin tuna in the Indian Ocean, are still unknown even though this information is essential to the development of effective and sustainable management strategies (Kerr et al., 2016; Bosley et al., 2019).

Several complementary techniques have been used to study the spatial structure and dynamics of marine fish, such as genetics, morphology, tagging and otolith microchemistry (Cadrin et al., 2014). Among them, the chemical composition of fish otoliths (i.e., earbones) has proved to be a useful method to study the origin and movement of yellowfin tuna in other oceans (Wells et al., 2012; Rooker et al., 2016; Kitchens et al., 2018). The approach relies on two assumptions: (1) during otolith formation material is accreted and preserved as fish grows, and (2) the chemical composition of the otolith is related to the physicochemical water mass inhabited by the fish at time of deposition (Campana, 1999). As such, the chemical composition of the otolith material deposited during early life stage of the fish, may serve as a natural marker of fish nursery origin. Particularly, oxygen isotopic signatures in otoliths of marine fishes are often liked to water mass properties, and variations in otolith $\delta^{18}O$ closely reflects the ambient experience by the fish (Trueman and MacKenzie, 2012; Darnaude and Hunter, 2018; Macdonald et al., 2020).

In the present study, we examined oxygen isotope composition of early life otolith material from yellowfin tuna captured across the Indian Ocean. Our aim was to test whether young of the year (YOY) yellowfin tuna captured in three different nursery areas of the equatorial Indian Ocean could be discriminated based in the isotopic composition, to then predict the nursery origin of older individuals captured elsewhere. Ultimately, this information can be useful to investigate the connectivity of this species in the Indian Ocean.

2. Material and Methods

2.1. Fish sampling

Yellowfin tuna (n=180) were sampled across the Indian Ocean at seven sampling locations (Fig. 1; Table 1). Samples were obtained by scientists or scientific observers directly on-board purse seine and longline vessels or at port during two consecutive years (2018 and 2019), as part of a collaborative research project on Population Structure of Tuna, Billfish and Sharks of the Indian Ocean (PSTBS-IO). Samples were classified as young of the year (YOY, < 40 cm FL), juveniles (40-75 cm FL) and adults (>75 cm FL) according to the age-length key relationship described in Eveson et al. (2015) and maturity threshold in Zudaire et al. (2013).

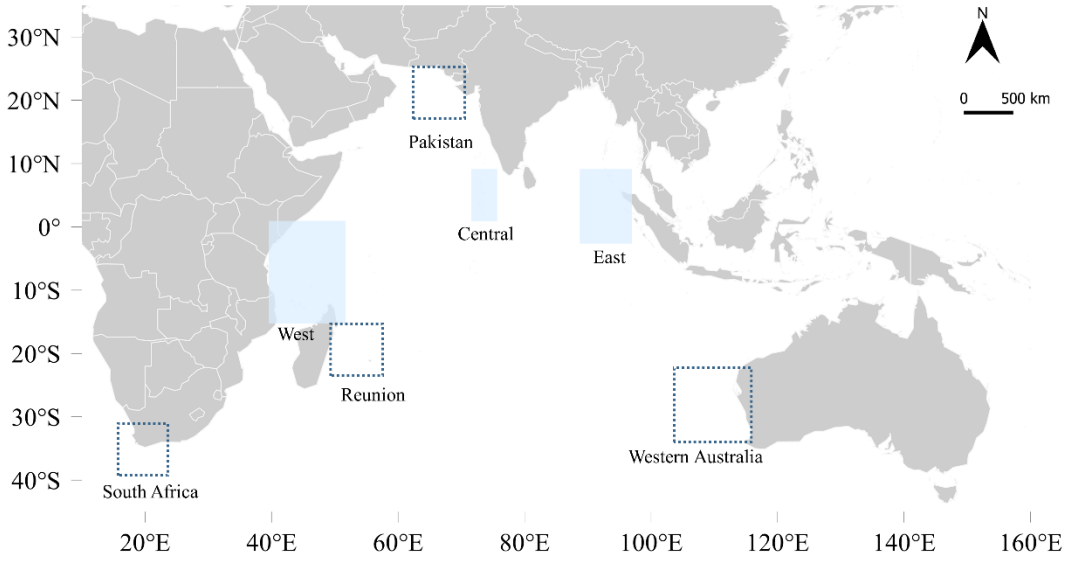

Figure 1. Sampling distribution of yellowfin tuna (*Thunnus albacares*) in the Indian Ocean. Shaded boxes represent nursery areas were young of the year (YOY) were captured from, and dotted boxes represent areas were juveniles or/and adults were captured.

Table 1. Number, sampling period, size and estimated ages of yellowfin tuna (*Thunnus albacares)* at each sampling area. Size is fork length (FL) in cm.

Location	N	Sampling dates	FL range (cm)	Life stage classification
West nursery	51	Mar-Apr 2018 Mar-Apr 2019	26-37.5	YOY
Central nursery	31	Ago 2018 Feb 2019	28-36	YOY
East nursery	31	Apr 2018 Nov 2019	19.5-34	YOY
Pakistan	12	Sep 2018	64-75	Juvenile
Reunion	16	Dec 2017	47-50.5	Juvenile
Reunion	12	Feb-Mar 2018 Feb 2019	124.5-169	Adult
South Africa	19	Mar-May 2018	133-138	Adult
Western Australia	8	May 2019	143-174	Adult

Life stage classifications according to the age-length key relationship described in Eveson et al. (2015) and maturity threshold in Zudaire et al. (2013)

YOY individuals were estimated to be less than four months at the time of capture based on length at (daily) age data from Proctor et al. (2019). Although migratory movements of YOY yellowfin tuna have not been documented in the Indian Ocean (Fonteneau and Hallier, 2015), it is thought that yellowfin tuna migrate from nursery areas in the Atlantic Ocean once they attain >60 cm FL (ICCAT, 2002). Little exchange of yellowfin tuna <50 cm FL between Maldives and the eastern Indian Ocean has also been described according to parasite and genomic data (Moore et al., 2019; Proctor et al., 2019). Due to all the above, we assumed that YOY yellowfin tuna were captured in their nursery area, and therefore, their early stage $\delta^{18}O$ signatures to represent nursery signatures. Conversely, for juvenile and adult tuna large movements can be expected within the Indian Ocean (Fonteneau and Hallier, 2015). Otolith collection available for this study comprised fish from different cohorts and hatched at different periods of the year, but otolith $\delta^{18}O$ temporal stability has been described by other authors (Rooker et al., 2008) and shows minimal decadal changes (Schloesser et al., 2009).

2.2. Otolith preparation and analysis

Sagittal otoliths were extracted, cleaned of adhering organic tissue, rinsed with ultrapure water, and stored dry in plastic vials. In the laboratory, the otoliths were embedded in two-part epoxy resin (Araldite 2020) and the blocks were polished with a series of grinding papers until the otolith core was exposed. The sections were sonicated for 10 minutes in ultrapure water (Milli-Q) and left to air for 24 h before being glued in a sample plate using Crystalbond thermoplastic glue (Crystalbond 509; Buehler).

Microsampling of otolith powder for oxygen stable isotope ($\delta^{18}O$) was performed using a high-resolution computerised micromill (New Wave MicroMill System, NewWave Research G. C. Co., Ltd, Cambs, UK). The length of the smallest yellowfin tuna (19.5 cm FL) otolith section was used to create a template that was then used for the remaining otoliths, to ensure that the same portion of the otolith was analysed in every fish (approximately two months of life according to the back-calculated age estimates). Ten drill passes were run at a depth of 50 µm per pass over a preprogrammed drill path using a 300-µm diameter carbide bit (Komet dental; Gebr. Basseler, Lemgo, Germany). Powdered material was then analysed for $\delta^{18}O$ on an automated carbonate preparation device (KIEL-III, Thermo- Fisher Scientific, Waltham, MA, USA) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252, ThermoFisher Scientific) at the Environmental Isotope Laboratory of the University of Arizona. $\delta^{18}O$ values were reported according to standards of the International Atomic Energy Agency in Vienna and represent ratios of 18O/16O in the sample relative to the Vienna Pee Dee Belemnite (VPDB) scale. The isotope ratio measurement is calibrated based on repeated measurements of NBS-19 and NBS-18 and precision is ± 0.10 ‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$ (1 sigma).

2.3. Statistical analysis

A Kruskal-Wallis rank sum test was used to explore variations in $\delta^{18}O$ in YOY yellowfin tuna otoliths from the three different nursery areas (West, Central, East), as the data did not meet homoscedastic assumptions. Post-hoc comparisons were performed using pairwise Wilcoxon rank sum test. The signatures of juvenile yellowfin tuna from Pakistan and Reunion were

compared between them (Mann-Whitney-Wilcoxon test), and with $\delta^{18}O$ values in YOY tuna from the three nursery areas (pairwise Wilcoxon rank sum test). The analysis of juvenile yellowfin tuna $\delta^{18}O$ composition showed that samples from Pakistan had sufficiently distinct signature from any other nursery (see Results) and, therefore, incorporated to the baseline sample. Quadratic Discriminant Function Analysis (QDFA) was performed to test the ability of $\delta^{18}O$ data to discriminate between areas in the baseline. Data was split into a training dataset (75%) and a testing dataset (25%), and this procedure was randomly repeated 1000 times. At each time, the rate of cross-validation classification success (i.e., rate of correct predicted membership to locations in which the fish were captured) was calculated, and mean values were extracted. Kappa (κ) value was also calculated, which is a method that accounts for the agreement occurring just by chance (Titus et al., 1984). QDFA was also used for adult assignment back to their nursery of origin. QDFA generates the probability that an individual fish belongs to a group presented in the baseline using the estimated discriminant model. Individuals with <70% probability of belonging to the assigned nursery were labelled as "unclassified".

3. Results

Early life otolith $\delta^{18}O$ signatures in YOY yellowfin tuna were distinct between the three nursery areas (Kruskal-Wallis test, $P<0.001$), with values decreasing from west to east direction of locations (Fig. 2). Distinct $\delta^{18}O$ isotopic composition between juvenile fish from Pakistan and Reunion were also evident (Mann–Whitney–Wilcoxon test, $P<0.001$). In addition $\delta^{18}O$ composition of juvenile fish captured in Reunion showed that these fish have an isotopic signature that resembled the nearest nursery, the West (Pairwise Wilcoxon Rank Sum test, $P=0.81$), while fish captured in Pakistan possess an isotopic signature that is distinct from any other nursery (Fig. 2).

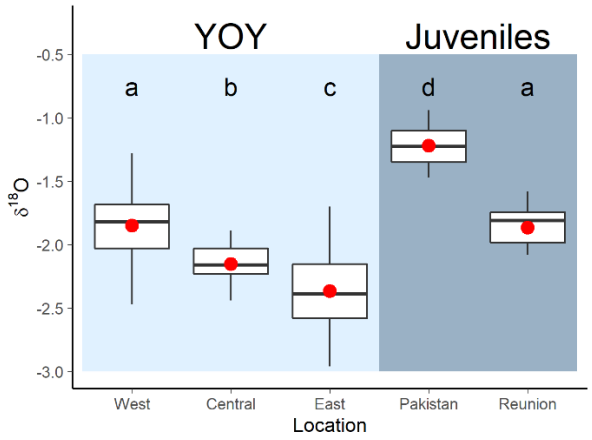

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Figure.2 Boxplots showing otolith early life $\delta^{18}O$ composition of YOY (light blue) and juvenile (dark blue) yellowfin tuna (*Thunnus albacares*) from the Indian Ocean. Letters identify significant differences (Pairwise Wilcoxon rank sum test, $P<0.05$) between means. Inter quartile range (25th and 75th percentile) is shown by extent of boxes and error bars represent 10th and 90th percentiles. Median (50th percentile) and mean values are shown in boxes as black lines and red dots, respectively.

Therefore, the early life $\delta^{18}O$ signature of Pakistan was considered as an additional area to be included in the baseline sample, although the exact geographical location of the nursery area they represent cannot be determined. Overall classification of individual fish back to their corresponding area in the baseline sample was of 68% and $\kappa=0.62$, which indicates a substantial agreement. Classification success varied considerably among areas (Table 2). The highest classification success (90%) was detected for fish from Pakistan and the lowest (49%) for fish from the Central nursery, which were often confounded with fish from West or East nurseries. Fish from the latter two nurseries showed a 70% and 79% classification success back to their nursery areas, respectively.

Table 2. QDFA classification success (%) fror yellowfin tuna (*Thunnus albacares*) in the baseline sample, based on early life otolith $\delta^{18}O$ composition.

	Pakistan	**West**	**Central**	**East**
Pakistan	**90**	4	0	0
West	10	**70**	27	4
Central	0	18	**49**	17
East	0	9	24	**79**

Data represent the percentage (%) of individual fish from the area of capture (column) assigned to each area (row). Bold values are correctly assigned.

Otolith $\delta^{18}O$ signatures of adult yellowfin tuna was compared with the four baseline signatures described, to predict the nursery origin of adult fish and resolve the potential production of each of the nursery grounds (Fig. 3). Most of adult individuals (24 out of 39) were derived from the West nursery. To lesser extent, some adults were also predicted to be derived from the same nursery as fish from Pakistan (5 out of 39). Both West and Pakistan signatures were detected in the three adult capture areas analysed. The Central and East nursery origins were not detected in any of the adult samples with a >70% of probability. Finally, out of the 39 adults analysed, 11 were designated as unclassified. The number of unclassified fish was especially high in samples collected in South Africa (7 out of 19).

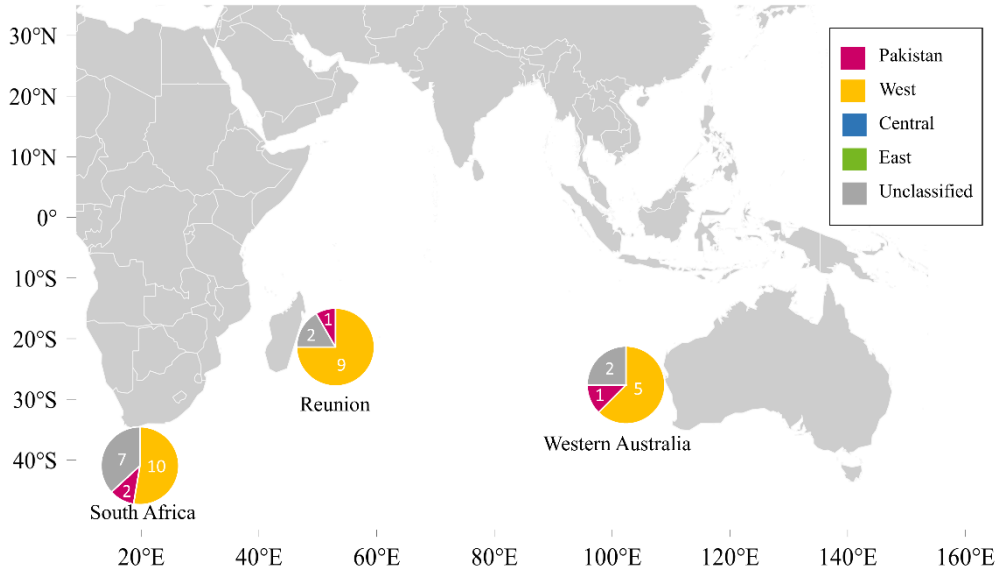

Figure 3. QDFA origin assessment (number by area) for adult yellowfin tuna (*Thunnus albacares*) from the three southern locations in the Indian Ocean, to one of the four areas in the baseline; Pakistan (purple), West (orange), Central (blue) and East (green). Individuals with assignments probabilities <70% to a baseline area were labelled as unclassified (grey).

4. Discussion

Under relatively uniform salinity conditions ambient sea surface temperature (SST) is an accurate proxy of otolith $\delta^{18}O$ (Kitagawa et al., 2013). Otolith composition of YOY yellowfin tuna from the Indian Ocean followed the expected trend for $\delta^{18}O$, presenting higher values in the western nursery (expected lower water temperatures, under the influence of the seasonal Somali upwelling) and decreasing towards the east (expected higher water temperatures, from the

Indonesian throughflow). The sizes of juveniles analysed in this study ranged from 47 to 75 cm FL and although they are not in spawning condition yet (Zudaire et al., 2013), yellowfin tuna of this length are capable of large migrations in search of foraging grounds (Fonteneau and Hallier, 2015). Therefore, we expected the early life isotopic composition for both the juveniles from Pakistan and Reunion to reflect a mix of overlapping nursery origin signals. However, juveniles from Pakistan and Reunion possess very different isotopic signatures, suggesting that these fish originated from different nurseries and have different early life histories. The otolith isotopic composition of juveniles from Reunion resembled that from the closest known nursery, the West, suggesting retention of juvenile fish near this area. High retention of juvenile fish near to their closest nursery area has also been reported for yellowfin tuna of the Pacific Ocean (Wells et al., 2012; Rooker et al., 2016). Interestingly, the nursery signature of juvenile fish from Pakistan was very different from any other nursery signature. Although is not possible to determine where the nursery of area of this fish is located because fish of this lengths area able to large scale movements (Hallier and Fonteneau, 2015), observed results could indicate the possible existence of a nursery area in this region. The elevated $\delta^{18}O$ signature in the samples from Pakistan can be related to the cold environment when coastal upwelling are triggered all around the North Arabian Sea at the onset of the summer monsoon (June) (Schott et al., 2002). We are not aware of any spawning ground of yellowfin tuna described in this area, but Barth et al. (2017) found that yellowfin tuna from the Arabian Sea (here Pakistan) were genetically isolated from yellowfin tuna from other areas of the Indian Ocean.

Estimates of nursery origins of adult fish predicted that most of the individuals analysed were derived from the West nursery, which highlights the importance of this area for yellowfin tuna production in the Indian Ocean. Again, high levels of regional fidelity were detected in adult fish from Reunion. Fish with West nursery origin were also found among adult fish collected in South Africa. This connection was also noticed during the Regional Tuna Tagging Program of the Indian Ocean (RTTP-IO), where a few yellowfin tuna tagged in Tanzania were recovered in the Agulhas current, along the South African coasts (see Fig 10, Fonteneau and Hallier, 2015). A genomic

analysis carried out by Mullins et al., (2018) also found high levels of Indian Ocean recruits among South African yellowfin tuna. A substantial number of unclassified fish were also identified in South Africa, and to a lesser extent in Reunion or Western Australia samples. While this might be a result of the $\delta^{18}O$ overlap in the described baseline, it is also possible that individuals from other nurseries not sampled in this study are present in the adult mixed sample, from the Indian or from the Atlantic or Pacific Oceans. In addition, few adults with Pakistan like signature were predicted at each of three adult locations sampled, suggesting that, as adults, some movements out of Pakistan area may occur. No fish from the Central or East nurseries were detected in the adult mixed samples of the three southern locations, which may imply limited movements outside this nursery areas, or movements towards norther latitude feeding grounds (i.e. Arabia Sea, Bay of Bengal) not sampled in this study. Limited movements outside the Maldives (were the Central nursery is) have also been described for some tagged yellowfin (Kolody and Hoyle, 2013).

5. Conclusions

Early life otolith oxygen stable isotope composition proved to have the potential to discriminate between three different nursery areas of yellowfin tuna in the Indian Ocean (West, Central and East). As such, it could be a useful tool to investigate further questions regarding yellowfin tuna connectivity and inform management decisions which aim to control the origin of harvest. Preliminary results suggest high levels of local residency among juvenile yellowfin tuna captured in Reunion, but also that juveniles captured in Pakistan did not resemble to fish from any of the nurseries sampled. Predicted contribution of the areas in our baseline sample (West, Central and East nurseries + Pakistan) to the adult sample was not proportional, with substantially higher West nursery contribution in the three adult locations sampled. This issue should be further investigated, as it might have implications for the management of this species. Analysing YOY from known spawning areas over several years would set up a baseline for matching otolith early life stage signatures from older fish. Further research on yellowfin tuna stock structure using otolith microchemistry should analyse the provenance of adult individuals, to investigate the

contribution of different nursery regions to fishery catches, but also target adult fish in spawning condition at the different nursery areas, to investigate the degree of spawning area fidelity and exchange between nurseries. This information will be essential to inform sustainable management decisions.

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