Universitat d'Alacant
Universidad de Alicante

Department of Marine Science
Faculty of Science

A socio-ecological and economic approach to tropical tuna fisheries in the Mozambique Channel

Presented by

Anildo Naftal Nataniel

Thesis submitted to aspire Philosophy Doctoral degree at the

University of Alicante

Doctoral Thesis Conferring the Title of

"International Doctor"

Doctoral Program in Marine Science and Applied Biology

Thesis Directors

Dr. Maria Soto Ruiz

Dr. Jon Lopez Jimeno

Funding: The research carried out in this Dr. Philos Thesis has been financed or received founds from World Wide Fund - Russel E. Training Education for Nature Program, Western Indian Ocean Marine Association, European Union under Erasmus+ mobility program ka107, and Eduardo Mondlane University.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisors Maria Soto Ruiz and Jon Lopez Jimeno for motivating, supervising and supporting me throughout this PhD. This is extended to Priscila F. M. Lopes and Maria Grazia Pennino for their patience on technical and scientific guiding in specific chapters of this thesis. I am deeply grateful to the fourth of you for guiding my progress as a researcher and developing my scientific criticism, and for your patience with me and my many mistakes.

Special thankfully to Professor José Luis Sanchez Lizaso, for motivating, advising and tutored me from start until to the final stage on this adventure, and many other staff of the Fishermen Project group of University of Alicante for providing valuable advice and guidance in the early stages. My most sincere thanks to Professor Antonio M. Hoguane for his expertise, advices, help, motivation, and opportunity offered to me to progress for doctoral studies and professional skills, and all the team from School of Marine and Coastal Science at Eduardo Mondlane University.

The input of many researches and friends has been valuable to my research along the way, especially the internship and study visits during the stages I have done in different institutions. In Spain, thanks go to Directors of Spanish Oceanographic Institute in Madrid, Eduardo Balguerías Guerra and Malaga, Jorge Cristobal Baro Domínguez for hospitality, hosting, assistance, and all information and data provided every time I came for thesis development, as well as all of those at the IEO whose expertise and friendship inspired me. I am also thankful to the AZTI-Tecnalia director (Rogelio Pozo) in the Basque Country and all the staff for kindly helping and hosting me in the earlier stages of this thesis. In Mozambique, sincere thanks go to IIP experts Jorge Mafuca (director), Osvaldo Chacate, Rui Mutombe, and Sergio José for data and information provided related to tuna fisheries in Mozambique, guiding to field work and with small-scale fisheries. Thanks also go to Mozambique

Fisheries Ministry, particular to Narci Nuro de Premegi (Fishery Secretary), Eugénio Antonio (Fishery Economy National Director), Cassamo Junior and Maria Isabel (Directors of Fisheries at Provincial level) for the technical orientations for data collection in Mozambique used in this research. Also, in Mozambique, my thanks addressed to all village's authorities, and small-scale fishers covered in this work during the interviews conducted for data collection.

Finally, I would like to thank my family: my mom Argentina Marcos, my dad Naftal Nataniel and my elder sister Olivia Nataniel and young brothers Cremildo Nataniel and Benildo Nataniel in memories. For my old brother Arsenio Nataniel, my siters, nieces and nephews whose motivated and encouraged me until succeeding on this hard road. You are the best family anyone could wish! Thank you. Special thanks must also go to Stella Osório Fosenca who shared her life with me and her Fonseca family, for all the opportunities you have given me in life, believe in me and encouraged me, support me all the time and remind me every day of what it is really important in life. Wherever you are, a small part of this dissertation is also yours. Last but not least, thank you Lidia Uqueio for your patience, fun moments, encouragement, believing in me and your unlimited support. Now, is time to celebrate!

Funding Sources and Support

The research carried out in this Dr. Philos Thesis has been developed in IEO - Spanish Oceanographic Institute with the collaboration of AZTI-Tecnalia, Eduardo Mondlane University, and it has been financed or received contribution for thesis development from:

Spanish Oceanographic Institute (IEO). Puerto pesquero s/n. Fuengirola, 29640 Málaga, España. The IEO was the host institution for thesis development, with main contributions on data provisioning, thesis supervising, and providing internship when it was necessary to work closely to the supervisor.

AZTI is a scientific and marine technological centre, Herrera Kaia, Portualdea z/g 20110, Pasaia, Gipuzkoa, Spain. The AZTI was the institution which provided very good environmental for internship and get introductory on modelling for starting data analysis, and working with supervisor in all issues related to thesis development

World Wide Fund (WWF) - Russel E. Training Education for Nature Program, 1250 24st St. NW, Washington, DC, 20037 - 1193, USA, worldwildlife.org. WWF was the main funding source which provided fellowship and research funds for field data collection

Western Indian Marine Association (WIOMSA) under the Marine Research Grant Program (MARG - II), Zanzibar, Tanzania, www.wiomsa.org. WIOMSA helped round trip travel between Mozambique and Spain and living expensive in Spain in some development stage of the thesis under MARG - II scheme.

European Union under Erasmus+ mobility program ka107, between University of Alicante (Spain) and Eduardo Mondlane University (Mozambique), Alicante, Spain. The mobility funds contribute to approach the candidate to their supervisors during the research activities

Eduardo Mondlane University (UEM) - School of Marine and Coastal Science, Quelimane, Mozambique. www.marine.mz. Av. 1 de Julho, Chauabo Dembe. The UEM supported the candidate to contact the fishing authority for fishery data gathering, field data collection with small-scale fisheries in Mozambique. The UEM also provided the environmental working and supervising his research activities.

Part of the information in this Dr. Philos thesis has been submitted for publication in the following peer-reviewed international scientific journals:

Nataniel, A., **Lopez**, J., **Soto**, M. (Accepted for Publication in Fishery Research). Modelling seasonal environmental preferences of tropical tuna purse seine fisheries in the Mozambique Channel.

Nataniel, A., **Pennino**, M.G., **Lopez**, J., **Soto**, M. (under review in Fisheries Oceanography). Modelling the impacts of climate change on skipjack tuna (*Katsuwonus pelamis*) in the Mozambique Channel.

Nataniel, A., **Lopes,** P. F M., **Lopez**, J., **Soto**, M. (under review in Fisheries Management and Ecology). Socio-ecological and economic aspects of tropical tuna fisheries in the Mozambique Channel - Insight from Mozambique.

Please cite this document as:

Nataniel, 2021. A socio-ecological and economic approach to tropical tuna fisheries in the Mozambique Channel. PhD thesis, Department of Marine Science and Applied Biology, University of Alicante, San Vicent del Raspeig, Alicante, Spain, 177p.

List of Acronyms

AAIW	Antarctic Intermediate Water
AC	Agulhas Current
AIC	Akaike Information Criterion
APECOSM-E	Apex-Predator-Ecosystem-Model-Estimation
BET	Bigeye Tuna
EDF	Effective Degree of Fredom
FADs	Fishing Around Aggregating Devices
FSC	Free Swimming Schools
GAM	Generalized Additive Model
GLM	Generalized Linear Model
GVC	Generalized Cross Validation
IEO	Oceanographic Spanish Institute
IOTC	Indian Ocean Tuna Commission
IPCC	Intergovernmental Panel on Climate Change
IRD	Institute pour le Reserche and Developpment
IUU-fishing	Illegal, Unreported and Unregulated Fishing
KSS	Kolmogorov-Smirnov statistic
MARSS	Multivariate Autoregressive State-Space Modeling
MZC	Mozambique Channel
ML	Marginal Likelihood
NADW	North Atlantic Deep Water
NIDW	North Indian Deep Water
netCDF	Network Common Data Form
PSU	Practical Salinity Unity
RCP	Representative Concentration Pathways
REML	- Restricted Maximum Likelihood
RMSE	Root Mean Square Error
RSW	Read Sea Water
SKJ	Skipjack Tuna
SSF	Small-Scale Fisheries
SST	Sea Surface Temperature
SEC	South Equatorial Currents
WIO	Western Indian Ocean
WWF	World Wide Funding
YFT	Yellowfin Tuna

Table of Contents

Lista of Figures

List of Tables

Resumen

El Canal de Mozambique (MZC), se encuentra en la parte suroeste del Océano Índico, al este de Mozambique, oeste de Madagascar y al sur del archipiélago de Comoros. El área de MZC se encuentra dentro de las latitudes 10ºS y 26ºS, donde se da una estación de invierno seca y fresca entre marzo y agosto, y otra estación húmeda y cálida de septiembre a febrero.El MZC es estrecho en la parte central con 430 km de ancho y alcanza un ancho máximo de 1000 km en la latitud 20ºS. El canal tiene ~ 3000 m de profundidad con una longitud de ~ 1600 km, con plataformas continentales estrechas. Los procesos oceanográficos se caracterizan por un mecanismo complejo de circulación de masas de agua, como la posible dilución y mezcla sugeridas entre las corrientes hacia el norte (p. Ej.: Aguas Profundas Frías del Atlántico Norte - NADW y Aguas Intermedias Antárticas - AAIW), corrientes hacia el sur (p. Ej.: Aguas Salinas del Mar Rojo - SW y Aguas Profundas del Norte de la India - NIDW) y corrientes ecuatoriales del sur (SEC) alrededor de la cuenca del arquipelago de Comoros. Además, hay efecto del ciclón y los remolinos anticiclónicos generados en el área más al norte de MZC que transporta sal y aguas cálidas de la capa superior alimentadas por la corriente ecuatorial sur que circula hacia el sur y se fusiona con las corrientes de agua intermedias de Agulhas en el extremo sur del canal. También, el agua cálida (SST ~ 28ºC - 30ºC) está relacionada con la formación de ciclones tropicales y la intensificación de las tormentas, promoviendo una alta evaporación, contribuyendo a incrementar la precipitación, turbulencia y mezcla de masas de agua en la región. Así, las interacciones de los procesos oceanográficos ambientales y biológicos, hacen del Canal de Mozambique un laboratorio natural idóneo para investigar la relación de las especies con el medio ambiente.

La circulación de las corrientes y otras características oceanográficas como la temperatura de la superficie del mar, las anomalías del nivel del mar, la salinidad, los frentes oceánicos, y su interacción con el aporte de nutrientes y las concentraciones de plancton, juegan un papel determinante en la red trófica del ecosistema marino y la diversidad de sus especies. Por lo tanto, el ecosistema marino del Canal de Mozambique se caracteriza por una alta diversidad de recursos pesqueros demersales y pelágicos, como cangrejos, camarones, calamares, bivalvos, tiburones, sardinas, anchoas, peces óseos, picudos, caballa y atún, junto con otras especies de aguas costeras de los países alrededor del Canal de Mozambique. En las zonas neríticas y oceánicas próximas al MZC las pesquerías artesanales y flotas industriales capturan túnidos tropicales de alto valor comercial (*Katsuwonus pelamis* - listado, *Thunnus albacares* - aleta amarilla y *Thunnus obesus* - patudo). La productividad de los túnidos tropicales está estrechamente relacionada con la variabilidad estacional e interanual de la circulación de los remolinos de mesoescala y las condiciones oceanográficas ambientales en el Canal de Mozambique. Por ejemplo, durante el invierno (marzo-junio), los cardúmenes de atún parecen alcanzar su punto máximo en MZC, atrayendo a los cerqueros para pescar en el norte del canal y, posteriormente, desplazarse entre Julio y Agosto hacia otro caladero. Por tanto, la sostenibilidad de las pesquerías de túnidos tropicales está determinada por la distribución espacio-temporal de las poblaciones de túnidos tropicales, caracterizada por un entorno inestable y cambios ambientales, así como la interacción de múltiples flotas. Las flotas industriales capturan túnidos tropicales que exportan principalmente al mercado internacional, mientras que las pesquerías de pequeña escala abastecen el mercado local de subsistencia.

En este estudio se analizan los efectos de las condiciones oceanográficas sobre la captura agregada de las tres principales especies de túnidos tropicales considerando las dos estrategias de pesca principales de la flota Española de cerco, es decir, la pesca sobre dispositivo artificiales de agregación de peces (FADs) y banco libre (FSC). Además, para cada estrategia de pesca, se investiga el desplazamiento de la agregación de captura bajo los efectos del cambio climático utilizando la captura de atún *Katsuwonus pelamis* como indicador biológico, y se discuten las implicaciones sociales y económicas del impacto climático sobre los países costeros alrededor del Canal de Mozambique. El atún *Katsuwonus pelamis* es el recurso pesquero ecológico más importante que sustenta las necesidades sociales y económicas de los países costeros del MZC y, por tanto, las predicciones de puntos críticos para mediados y finales de siglo bajo diferentes escenarios de cambio climático son resultados que deben ser considerados en los planes de conservación y gestión de este recurso. Además, se analizaron las tendencias en las capturas de atún de las flotas industrial y artesanal y el impacto de su interacción.

El objetivo general de esta investigación de tesis es mejorar nuestro conocimiento sobre los factores clave que impulsan la dinámica de las pesquerías de túnidos tropicales en el MZC, bajo un contexto que combina la acción e interacción de la flota de cerco industrial y la pesca a pequeña escala. Este objetivo general se concreta en una serie de objetivos principales, como son, investigar qué variables ambientales pueden explicar la agregación de la densidad de cardumen en un determinado hábitat, predecir la mayor agregación espacial de captura explotable bajo distintos escenarios de cambio climático, evaluar la evolución de las capturas de atún tropical y discutir los aspectos socio-ecológicos y socioeconómicos de las interacciones entre las flotas de cerco y la pesca artesanal. El objetivo de estos estudios es esencial para la conservación y gestión de los recursos tropicales explotados por distintas flotas tanto para fines comerciales como de subsistencia y establecer políticas hacia la sostenibilidad ecológica, social y económica con el fin de garantizar el bienestar de las comunidades de pescadores y naciones. Para el desarrollo del objetivo general, se han definido y resumido objetivos específicos de la siguiente manera: (i) investigar las relaciones entre los factores ambientales y la acumulación de cardúmenes de túnidos tropicales en hábitats marinos capturados por la flota Española de cerco sobre FADs o sobre FSC en el Canal de Mozambique; (ii) investigar la dinámica temporal y predecir los hábitats espaciales para la agregación de cardúmenes de túnidos o puntos críticos para la pesca en relación con sus preferencia ambientales;, (iii) investigar los cambios de distribución y agregación del *Katsuwonus pelamis* frente a los escenarios futuros de concentraciones representativas (RCP) de cambios climáticos para 2050 y 2100. Es decir, bajo los escenarios RCP2.6 y RCP8.5 optimistas y pesimistas de emisión de carbono respectivamente, dadas la importancia ecológica y socioeconómica de atún *Katsuwonus pelamis* (skipjack) en la región; (iv) discutir los cambios en las tasas de captura y socioeconómicos que afectan a las comunidades pesqueras considerando la incertidumbre asociada al cambio climático en el Canal de Mozambique; (v) describir las interacciones socioecológicas y socioeconómicas entre la pesca industrial y los sectores de la pesca en pequeña escala en las aguas costeras, en base a la información disponible de las pesquerías de Mozambique; (vi) explorar, desde el punto de vista ecológico, el efecto que ejercen la flota industrial en las poblaciones objetivo, así como el impacto socioeconómico en la pesca a pequeña escala, siendo esta, además, más vulnerable al cambio climático a lo largo de la costa de Mozambique. Estos objetivos comparten una meta práctica, ya que apuntan a proporcionar conocimiento científico ambiental y los impactos de la pesca de múltiples flotas en el atún tropical, y tienen consecuencias socioeconómicas de las comunidades de pescadores y naciones alrededor del Canal de Mozambique, y discuten los efectos y estrategias climáticos que podría abordarse para la adaptación o mitigación impuesta por los cambios climáticos. Además, los resultados de esta tesis pretenden impulsar la investigación futura sobre los impactos del cambio climático y las interacciones socioecológicas entre las flotas pesqueras en el marco de la gestión pesquera.

Los datos científicos utilizados en el análisis de capturas y esfuerzo de la flota española de cerco en el área del Canal de Mozambique se obtuvieron de las bases de datos del Instituto Español de Oceanografía (IEO) para el período de Febrero de 2003 a Junio de 2013 a partir de los cuadernos de pesca de la flota de cerco española, una vez corregida la composición específica de las capturas a partir de los datos detallados de la flota y el muestreo de puertos. Los datos de captura y esfuerzo de los cuadernos de pesca contienen información de los lances de pesca para FADs y FSC. Y estas información se utilizaron para investigar los efectos ambientales sobre la agregación de captura y para proyectar la distribución futura de la cardumen atún *Katsuwonus pelamis* en escenarios de cambios climáticos. Paralelamente a los datos de pesca, los datos ambientales para la misma subárea del MZC y el mismo periodo de tiempo se obtuvieron del consorcio MyOcean-Copernicus EU (marine.copernicus.eu) en formato netCDF. Para cada posición o fecha de lance de pesca se seleccionaron del archivo netCDF las siguientes variables: temperatura de la superficie del mar, gradiente de temperatura de la superficie del mar, altura de la superficie del mar, energía cinética de los remolinos, corrientes geostróficas, salinidad, concentración de clorofila-a, gradiente de la clorofila-a y concentración de oxígeno disuelto. La resolución espacio-temporal fue de 1/4° por día. Además de las variables oceanográficas, se incluyeron en el análisis variables espacio-temporales relacionadas con la abundancia o incluso con otros procesos ambientales encubiertos no incluidos en el modelo. Todas las variables se extrajeron del producto CMEMS GLOBAL_REANALYSIS_PHY_001_031, excepto clorofila-a y concentraciones de oxígeno que se descargaron del producto GLOBAL_REANALYSIS_BIO_001_029. Para predecir la distribución futura de la captura de *Katsuwonus pelamis* bajo escenarios de cambio climático, se utilizaron las proyecciones de temperatura superficial del Panel Intergubernamental sobre Cambio Climático (IPCC). En particular, se contemplaron dos escenarios de las Rutas Representativas de

Concentración (RCP) 2.6 y 8.5 para los años 2050 y 2100 (niveles de forzamiento radiativo de aproximadamente 2.6 y 8.5 Wm-2 para finales de 2050 y 2100, respectivamente) para la temperatura media mensual de la superficie del mar con una resolución espacial de 0.083º x 0.083º a partir de las bases de datos de Bio-ORACLE (http://www.bio-oracle.org). El escenario de emisión RCP2.6 (optimista) asume el menor cambio, con un aumento de temperatura de 1ºC para 2050 y 2ºC para 2100 y un aumento de salinidad de 0,5 psu y 1 psu para estos mismos años, respectivamente. El escenario RCP8.5 (el más pesimista), por el contrario, predice cambios más severos, con un aumento de temperatura de 1.5 ° C para 2050 y casi 3 ° C para 2100, y un aumento de salinidad de 1 y 1.5 unidades para estos mismos años, respectivamente.

Por otro lado, además de los datos de los cuadernos de pesca mencionados, se utilizó información de la Comisión del Atún del Océano Índico (IOTC) y se elaboró un cuestionario para explorar los conocimientos ecológicos tradicionales (TEK) de los pescadores con el fin de captar la percepción de los pescadores sobre la tendencia de las capturas y estudiar la interacción socioecológica entre la flota de cerco industrial y la pesca en pequeña escala en las aguas de Mozambique. En las comunidades de pescadores se realizaron los cuestionarios de forma presencial, lo cual permitió aportar calidad a la información a partir de la interacción entre el entrevistador y los entrevistados. El cuestionario constaba de cuatro partes: información personal (por ejemplo, edad, experiencia y educación), capturas de atún tropical (por ejemplo, composición por tamaño de las capturas, estacionalidad, tipos de artes, equipos y técnicas de pesca), aspectos socioeconómicos de la pesca de atún (por ejemplo, ingresos , empleos, cadena de valor, costo de pesca) e interacciones entre los pescadores en pequeña escala y las pesquerías industriales de cerco (por ejemplo, tipos de interacciones, uso de FADs, impactos potenciales). Los métodos para este estudio incluyeron una combinación de encuestas de opinión de expertos, entrevistas con informantes clave y muestreo de bola de nieve según las recomendaciones de la literatura. En las encuestas de opinión de expertos se selecciona a las personas más conocedoras o experimentadas de la comunidad para ser entrevistados. En el caso de este estudio, cuando fue posible, la comunidad ayudó a identificar informantes clave, es decir, aquellos que tenían información más específica y detallada sobre la captura de túnidos tropicales. A su vez, cada entrevistado sugirió los nombres de otros expertos locales, lo que se conoce como "muestreo de bola de nieve". Este método de muestreo fue especialmente eficaz dado que menos del 10% de los pescadores de cada comunidad de estudio se dedican al atún tropical. Además, también se consultó a las autoridades pesqueras, a los líderes de las comunidades y los informantes clave para recomendar a su vez a pescadores expertos de atún que podrían estar en disposición de ser entrevistados, dada la falta de bases de datos oficiales de las capturas tanto en las comunidades como a nivel general.

Todos los análisis estadísticos se realizaron mediante el software R versión 3.5.0. Para analizar la relación entre la captura y las variables ambientales, se realizó un análisis gráfico descriptivo de dichas relaciones en tiempo y en el espacio mediante el paquete “cloud”. Mediante árboles aleatorios (paquete “randomForest”) se realizó una selección de las covariables más significativas y se analizó la correlación entre ellas. Aquellas variables con estadístico de correlación de Pearson $|r| \leq -0.70$ y factor de inflación de la varianza (VIF) con umbral ≥ 3 se eliminaron del análisis. Se analizó la mejor distribución que se ajustaba a la captura o transformaciones de la misma para seleccionar el modelo y variable respuesta que dieran un mejor ajuste según el modo de pesca (FSC o FAD). Para ello se utilizó el paquete “fitditrplus” para determinar la mejor distribución y se emplearon los criterios de bondad de ajuste Akaike (AIC), test de Kolmogorov-Smirnov y gráficos de ajuste a diferentes distribuciones normal, lognormal y gamma. Se probaron diferentes niveles de agregación espacio temporal de los datos y, finalmente, los mejores ajustes se realizaron con datos de captura agregados mensualmente y promedio mensual de variables ambientales en cuadrículas de 1/4 °. Se utilizó el paquete raster de R que permite crear diferentes cuadrículas de escala. Se emplearon modelos aditivos generalizados (GAM) para examinar los efectos de las variables ambientales en la captura de atún agregada para cada modo de pesca (es decir, FADs y FSC), y para predecir los puntos críticos donde la captura de atún se acumuló en el canal de Mozambique.

En los modelos GAM se utilizó como variable respuesta la transformación logarítmica de la captura total, es decir, log (Captura + 1)), perteneciente a la familia de distribución normal y con función de enlace la identidad mediante el paquete mgcv de R. La bondad de ajuste de los modelos se evaluó mediante los criterios de porcentaje de desviación explicada, AIC, validación cruzada generalizada (GCV), diagnóstico de los residuos. Para ello se dividió aleatoriamente las observaciones en 10 grupos, siendo el primero el conjunto de validación y el resto de los 9 grupos el conjunto de ajuste del modelo. Para evaluar la capacidad predictiva del modelo se calculó la tasa de error cuadrático medio (RMSE) en el conjunto de validación. Para visualizar los resultados en figuras o mapas se emplearon los paquetes ggplot2, raster, mgcv y mgcViz y GISTools en R.

Los mismos procedimientos de construcción de modelos GAM en R, se utilizaron posteriormente para predecir la futura redistribución de las capturas del listado (*Katsuwonus pelamis*) bajo los escenarios de cambio climático. Pero, la distribución de los datos de las capturas de Katsuwonus *pelamis* muestra que ambos tipos de lances cerqueros (FAD y FSC) comparten los mismos caladeros de pesca en el área. Debido a los caladeros compartidos y la incertidumbre para discriminar entre cardúmenes de *Katsuwonus pelamis* libres y asociados, todos los datos de pesquerías se combinaron en este estudio para construir un único modelo predictivo. Finalmente, el modelo se construyó con datos ambientales y se utilizó para proyectar la distribución de la captura de barrilete en el futuro (2050 y 2100) de acuerdo con los escenarios de cambio climático RCP2.6 y RCP8.5. Los escenarios de cambio climático RCP2.6 y RCP8.5 predicen los aumentos más bajos y más altos en las temperaturas globales de las concentraciones de gases de efecto invernadero, respectivamente. Las variables climáticas disponibles en BiO-ORACLE se utilizaron para predecir escenarios futuros (es decir, temperatura de la superficie del mar-SST), mientras que las variables restantes utilizadas para construir el modelo se establecieron en cero dado que el objetivo era predecir en función de los cambios de SST: el principal proxy de los escenarios de intensidad del cambio climático. La SST ha sido considerada uno de los mejores factores para predecir el nicho ecológico del atún barrilete, ya que influye en las habilidades fisiológicas y el comportamiento migratorio del barrilete, afecta el forraje de alimentación óptimo y las tasas de crecimiento, y limita la agregación de desove entre los cardúmenes tanto en aguas latitudinales norte como sur temperaturas promedio> 24ºC isotermas. Además, la SST es un buen proxy o está conectada a otras variables y procesos ambientales. Además, los datos de SST de Bio-ORACLE se han utilizado ampliamente para predecir la distribución potencial de especies marinas en diferentes escenarios de cambio climático. Los cambios en la distribución del barrilete se evaluaron estimando las diferencias en las predicciones espaciales de cada celda de ¼º cuadrado entre los escenarios futuros proyectados y los del período de referencia.

Por último, para analizar los aspectos socio-ecológicos y económicos de las pesquerías de túnidos tropicales en el Canal de Mozambique desde la perspectiva de Mozambique, se seleccionaron los datos de las flotas industriales de cerco que operan en el la zona económica exclusiva (ZEE) de Mozambique, tanto los diarios de pesca de IEO como los datos globales de la IOTC. Se empleó software QGIS 3.4 (2018) para extraer los datos de captura de EEZ de Mozambique y el paquete ‘polyinorm' de R para la visualización de los datos. Para modelar el comportamiento de la flota, las tendencias de captura de atún y la CPUE se empleó `mgcv´para ajustar regresiones polinómicas de grado 3, que daban una medida de bondad de ajuste (R^2) mayor tanto en las tendencias de captura como en el diario de pesca y los datos comerciales. Por otro lado, con respecto a los datos de la pesca en pequeña escala, se investigó si el atún más grande (kg) capturado o visto (es decir, capturado por otro pescador) por los pescadores había cambiado con el tiempo, de acuerdo con sus propios recuerdos del tamaño y el año en que se produjo la captura. Se eligió el "atún individual más grande" como indicador ecológico que los pescadores recordaran porque las especies de túnidos tropicales a muchas veces se desembarcan mezclados con otras especies de peces, incluidos los túnidos pelágicos y neríticos, lo que dificulta la capacidad de los pescadores para diferenciar cuáles fueron las las mejores capturas exclusivamente de túnidos tropicales. Utilizar los recuerdos de los pescadores es una estrategia relativamente fiable para detectarlos cambios en las capturas (cantidades y tamaño de los peces) cuando las estadísticas oficiales no están disponibles. Las comunidades también se agruparon en regiones para acceder a las percepciones ambientales y locales de los pescadores sobre los impactos sociales y económicos de la pesca del atún en sus comunidades. Se asumió que los pescadores de comunidades cercanas faenaban en un entorno marino similar y, por lo tanto, se asumió que compartían estrategias de adaptación, comportamientos específicos, culturas pesqueras y acuerdos de autoorganización similares arraigados en ese entorno en particular. Por lo tanto, el análisis de datos se agrupó en cuatro comunidades en el extremo norte (10ºS - 13ºS), tres en el norte (13ºS -15ºS), tres en el sur (21ºS - 26ºS) y ningún muestreo entre 15ºS y 21ºS, ya que los informantes clave declararon que no hubo capturas de túnidos tropicales en esa franja.. Se analizaron además las otras estadísticas relacionadas con el análisis de los indicadores sociales (por ejemplo, el empleo de los pescadores) y económicos (por ejemplo, los ingresos de los pescadores).

Los resultados de estudios mostraron que efectos más significativos que se observaron sobre la captura alrededor de los FAD fueron las interacciones espacio-tiempo, temperatura y gradiente de temperatura, clorofila y gradiente de clorofila, energía cinética, la dirección de la corriente, la altura de la superficie del mar y la salinidad. Esta captura de túnidos tropicales asociada a FAD alcanzaba su máximo en la costa de Mozambique entre las latitudes 18ºS y 24ºS entre febrero y principios de marzo. Desde finales de marzo hasta mayo, la captura se concentraba en la costa oeste de Madagascar entre las latitudes 12ºS y 17º S, y de junio a agosto se acumulaba en la zona norte del Canal de Mozambique por debajo de 12ºS. Los efectos observados sobre la captura asociada a banco libre fueron también las interacciones espacio-tiempo, temperatura de la superficie del mar y gradiente de temperatura, y los efectos individuales de la salinidad, altura de la superficie del mar y concentración de clorofila. Para FSC se observó que en febrero la densidad de captura de atún se concentraba en el norte del Canal de Mozambique. Se observó una alta captura en abril y mayo, y de manera similar a la estrategia FAD, el modelo detectó que los cerqueros FSC comienzan a salir del Canal de Mozambique hacia otro caladero entre junio y agosto. Se observó una alta densidad de captura en el norte del canal de Mozambique, con un núcleo en la costa noroeste de la isla de Madagascar a una longitud de 40ºE a 46ºE y una latitud de 10ºS a 20ºS. La captura asociada a FADs domina la costa noroeste de Madagascar, mientras que los valores de FSC fueron muy altos principalmente en el norte de las islas Mayotte y Comoras, cruzando en sentido antihorario hasta la costa de Mozambique y entre los 17ºS y 19ºS de latitud.

Con respecto a los escenarios de cambio climático, entre 2003-2013 (en adelante: RPS - período de referencia del estudio) las áreas de pesca de *K. pelamis* cubrieron, aproximadamente, el 25%, en el Canal de Mozambique. Se estimó que los cambios generales de área proyectados para la agregación de captura de *K. pelamis* serían ~ 84%. Cuando se proyecta utilizando el modelo de captura de *K. pelamis*, las diferencias entre los escenarios futuros y actuales bajo los escenarios de cambio climático RCP2.6 y RCP8.5 predijeron pérdidas de capturas, sin cambios en las capturas y ganancias de capturas dentro del MZC (Figura 3). En particular, el escenario, RCP2.6 predijo pérdidas de captura de barrilete de ~ 46% y ~ 43% en latitudes norte (<20ºS) desde la RPS hasta finales de 2050 y 2100, respectivamente. Se proyectó una expansión positiva de ~ 47% hacia latitudes sur (> 20ºS) para fines de 2050 y 2100, mientras que entre 2050 y 2100 no se pronostican cambios en las capturas de En particular, el escenario en ~ 91% de los caladeros. En relación al escenario RCP8.5, para 2050 se proyectaron pérdidas de capturas (~ 43%) y propagación positiva (47%) en latitudes tanto por debajo como por encima de 20ºS. Para 2100, el modelo predijo el desplazamiento positivo de anomalías positivas (84%) de las capturas de atún, es decir, la recuperación del atún en la latitud <20ºS y se proyectó que estas aumentarían en las áreas sur del MZC, con una agregación particularmente alta de cardúmenes de atún por encima de 24ºS. Se pronosticó una pérdida y sin cambios en las capturas de atún en el área estrecha entre 20ºS y 24ºS que cubre un área de ~ 16%. Una comparación entre las proyecciones futuras de 2050 y 2100 revelaron que las capturas de *K. pelamis* se perderían o no cambiarían alrededor de 20ºS-25ºS en casi 24%. Por el contrario, en las áreas <20ºS y> 25ºS se proyectaron las anomalías de captura positiva (~ 76%), la mayoría acumulada en la parte norte del MZC. Las proyecciones muestran un desplazamiento caracterizado por recuperación de la captura (<20ºS) y expansión por encima de 25ºS.

El análisis de proyección de pesquería de K. *pelamis* bajo escenarios de cambios climático en las naciones costeras a lo largo de la MZC que tienen una dependencia de moderada a alta de la pesca en lo que respecta a sus economías nacionales, ingresos por exportaciones y consumo de pescado están sujetos a la vulnerabilidad climática y con capacidad de adaptación baja. Por lo tanto, se alienta a los pescadores, administradores de pesquerías y tomadores de decisiones alrededor del Canal de Mozambique a tomar medidas para hacerlos más resilientes y adaptarse al cambio de incertidumbre socio-ecológica y socio-económica asociado con el cambio climático. Dado que muchos pescadores en pequeña escala se han dirigido principalmente a los túnidos y especies afines en la parte norte del Canal de Mozambique que es un área que se prevé que sea significativamente impactados, tendrán que adaptarse a esta nueva realidad, por ejemplo, apuntar a múltiples especies, cambiar sus temporadas de pesca o sitios de pesca o desarrollar nuevas estrategias de pesca. Para los pescadores con fuertes vínculos con sus comunidades, que no pueden o no quieren acercarse a estos nuevos caladeros de pesca, es posible que deban adoptar medios de vida más diversificados y flexibles, como incluir otras actividades o fuentes de ingresos distintas de la pesca. Por el contrario, las flotas industriales pueden responder a los impactos climáticos invirtiendo en tecnologías de pesca innovadoras y técnicas avanzadas para continuar pescando las especies objetivo originales. Se discutió también que el dilema para las partes interesadas de la pesca, es cuándo y cómo adaptarse o ser resilientes ante las incertidumbres de los recursos marinos y los efectos del inevitable cambio climático. Por lo tanto, las partes interesadas de la pesca que operan en el Canal de Mozambique deben desarrollar planes de ordenación pesquera preventivos para reducir la vulnerabilidad de las comunidades pesqueras, incluso si estos planes de adaptación no entran en vigor durante varios años. Las estrategias de adaptación y mitigación al cambio climático variarán según la pesquería, dado que el grado de exposición, sensibilidad, vulnerabilidad y capacidad adaptativa difiere según el ecosistema ecológico marino, las especies objetivo, las características operativas de la flota y los grupos sociales. Los enfoques para mejorar la resiliencia de los sectores pesqueros, como la cogestión adaptativa o la planificación espacial marina inclusiva, que se han propuesto para abordar la incertidumbre y aprovechar el conocimiento y el compromiso de los recursos pesqueros a múltiples escalas, pueden ser un buen lugar. para comenzar. Este estudio contribuirá a una mayor conciencia de los impactos del cambio climático en las pesquerías de alto valor ecológico y socioeconómico, como las pesquerías de atún listado en el MZC.

Las pesquerías industriales de cerco que capturan túnidos tropicales comenzaron en aguas de Mozambique en 1983. Entre 1983 y 2014, España y Francia realizaron capturas de 58,1 y 37,2 mil toneladas de túnidos tropicales, respectivamente, mientras que las flotas regionales (por ejemplo, Seychelles, Mauricio, Mayotte) en conjunto representaron alrededor de 10,9 mil toneladas, y en general, las flotas NEIPS (Países Bajos, Italia, Grecia, Portugal, Japón, Corea y otros), representaron casi 12,2 mil toneladas. La tendencia de la captura de atún tropical en aguas de Mozambique se caracterizó por un incremento de las capturas al principio de la pesquería hasta alcanzar valores máximos antes del año 2000 para descender posteriormente hasta la actualidad, independientemente de la fuente de datos (diario de pesca español detallado o datos comerciales generales). Por otro lado, la percepción de los pescadores a pequeña escala era de un descenso en las capturas al largo del tiempo. Las capturas españolas de cerco reflejadas en los diarios de pesca aumentan un 4,06% anual entre 1983 y 2000, seguido de un rápido descenso del 7,21% anual hasta 2014. Las capturas totales aumentaron primero a un ritmo del 1,65% anual entre 1983 y 1997, y posteriormente disminuyen alrededor de una tasa de 1,35% hasta el final del periodo. Los datos sugieren que las capturas han ido disminuyendo en general durante los últimos 15 a 20 años, aunque la variabilidad es mayor en los cuadernos de pesca (r2 = 0.51) que en las capturas totales (r2 = 0,45).

La UE ha contribuido al desarrollo del sector pesquero en Mozambique desde el año 1987 a partir de la firma de los primeros acuerdos de pesca (FPA) para las flotas de cerco y este desarrollo ha continuado mejorando hasta 2015. Por ejemplo, las contribuciones anuales de la UE para el desarrollo del sector pesquero local fueron 826.400 € y 1.087.100 € en 2007 y 2012, respectivamente, lo que corresponde, aproximadamente, a $ 680.000 en 2007 y $ 800.000 en PPA dólares de 2012 (PPA - paridad de poder adquisitivo en USD).

Los resultados de las encuestas a los pescadores concluyen que el peso del atún más grande capturado (en kilogramos) iba disminuyendo un 2,5% al año. A pesar de la tendencia decreciente, los pescadores refieren dos ejemplares de 100 kg cada capturados en 2008 y 2017. Los pescadores señalan una mayor presencia de atún tropical desde finales de diciembre hasta mayo en la región norte (<16ºS), mientras que en la región sur (> 21ºS) las capturas se producían principalmente entre finales de junio y noviembre. En general, los pescadores artesanales no percibieron mucha interacción en los caladeros de pesca de los cerqueros industriales y su propia actividad, aunque la situación es menos clara en la región sur, lo que sugiere que eventualmente existen algunos caladeros superpuestos. Los pescadores entrevistados nunca han visto FADs perdidos por los cerqueros industriales, ni utilizan FADs para atraer peces. Las interacciones socioecológicas entre la pesca industrial y en pequeña escala consisten en la competencia por las mismas especies de atún tropical. La ley de pesca en Mozambique, fija el límite por debajo de las 12 millas náuticas para los pescadores en pequeña escala, mientras que las flotas industriales pueden operar en alta mar Sin embargo, la ecología reproductiva de atunes tropicales, desove y desarrollo de juveniles ocurre en las zonas costeras, mientras que en la etapa adulta la mayoría de las especies de túnidos realizan migraciones espaciales y estacionales entre la costa y el mar, generando la competencia entre las flotas industriales y de pequeña escala.

En la pesca a pequeña escala, dependiendo del arte y área de pesca, el empleo generado varía El cerco pequeño genera empleo para entre 6 y 32 personas; las redes de enmalle entre 6 y 18 y en líneas de mano de 1 a 7 personas. En la región norte de Mozambique, la especie objetivo de muchos pescadores son los túnidos tropicales, mientras que, en el área sur, los pescadores tienen como especies objetivo tanto los túnidos tropicales como otras especies rentables económicamente. La fuerza laboral (FTE) medida en horas para un trabajador de Mozambique a tiempo completo se calcula que es equivalente a 8 horas / día x 5 días / semana x 4 semanas / mes ≈160 horas por mes.

En comparación la carga de trabajo en FTE para artes de línea de mano fue de alrededor de 3 FTE, aproximadamente 15 FTE en redes de enmalle y aproximadamente de 32 FTE en el cerco, es decir, las horas de trabajo son mayores para el oficio de la pesca. La carga de trabajo mayor correspondía a los pequeños cerqueros con >30 FTE veces mayor que el promedio de horas mensuales de un trabajador medio. La remuneración en los grupos de líneas de mano varió entre los 106 € y los 555 € para los pescadores y era de unos 644 € para un patrón en una buena temporada de pesca. Para redes de enmalle, los ingresos de los pescadores oscilaban entre los 245 € y los 371 € y llegan hasta los 793 € para un patrón o propietarios de barcos en temporada alta de pesca. Los pescadores de los pequeños cerqueros ganaban entre los 252 € y los 280 €, mientras que la compensación para los propietarios de embarcaciones estaba entre los 445 € y los 542 € en una buena temporada de pesca. Para los pescadores a pequeña escala, los ingresos en temporada alta de pesca eran mejores que los ingresos del personal del sector pesquero público (sin incluir los puestos de gestión bien remunerados) durante el período 2017-2019.

Finalmente, las conclusiones de estas tres etapas de investigación fueron las siguientes: (i) Entre las condiciones oceanográficas que determinaban los puntos críticos de captura para ambos tipos de pesca de cerco (FSC y FADs) en el canal de MZC se encontraban la temperatura de la superficie del mar y su variabilidad, la productividad, la altura de la superficie del mar y la las interacciones de las variables espaciales y temporales. Sin embargo, las corrientes geostróficas mostraron un efecto significativo solo para la acumulación de captura pescable en los FADs. El efecto dinámico de las variables oceanográficas ambientales sobre la acumulación de captura de túnidos tropicales a lo largo del Canal de Mozambique varía según el modo de pesca FAD y FSC. Los modelos predijeron hábitats preferidos para peces asociados con FADs entre 10ºS y 18ºS, con el núcleo, en general, en la costa noroeste de Madagascar. Las predicciones para el hábitat preferido en FSC muestran que el núcleo se encuentra principalmente en la parte norte del Canal de

Mozambique y también cerca de la costa de Mozambique entre las latitudes 10ºS a 16ºS. El modelo predijo un caladero de pesca parcialmente superpuesto entre los FADs y la el FSC, a pesar de la diferencia en las variables oceanográficas seleccionadas por cada modelo aditivo generalizado para establecer hábitats de pesca preferidos a lo largo del canal de Mozambique. Los resultados obtenidos de la relación entre el medio oceanográfico y la acumulación de captura de túnidos tropicales en hábitats marinos específicos en esta investigación destacan una conexión entre el estado biofísico de los océanos y las pesquerías de cerco de túnidos tropicales en el MZC, que, en última instancia, pueden contribuir mejorar el asesoramiento científico para la conservación adecuada de los recursos explotados por las flotas de cerco en el área, y apoyar la toma de decisiones y la gestión con base científica en un ecosistema oceánico en constante cambio como el Canal de Mozambique. (ii) En relación de la captura de *K. pelamis* bajo el escenario climático, los hallazgos sugieren que las variables biofísicas afectan la distribución de las capturas de barrilete en el MZC y que la distribución de las especies se verá afectada por el cambio climático, particularmente en la parte norte, con posibles implicaciones en las comunidades pesqueras locales e internacionales. El modelo proyectó la distribución del *K. pelamis* e bajo escenarios de cambio climático optimista (RCP2.6) y pesimista (RCP8.5). El escenario optimista proyectaba que las capturas de *K. pelamis* se desplazarían hacia la parte sur del Canal de Mozambique, entre las latitudes 19ºS y 25ºS, para el 2050, y que el cambio de distribución sería menor o sin cambios entre 2050 y 2100. En el peor de los casos (RCP8.5), los caladeros potenciales de pesca se proyectaron en latitudes >20ºS para 2050, y se pronosticó que probablemente se producirían anomalías positivas en latitudes <20ºS entre 2050 y 2100.

Además, para fines del siglo XXI, se observan signos de una alta distribución de las capturas. se espera fuera del MZC en latitudes >25ºS hacia las regiones templadas. Dado que se prevé que el cambio climático afectará la pesca de barrilete en el MZC, puede generar desafíos socioeconómicos para las comunidades pesqueras. Los estados costeros en el área de MZC deben fortalecer la gobernanza y promover políticas para construir resiliencia y aumentar la capacidad de adaptación de las pesquerías locales, nacionales y regionales para reducir su vulnerabilidad a los impactos climáticos. El presente estudio contribuirá tanto a una mayor conciencia sobre el cambio climático entre las partes interesadas como a la necesidad de desarrollar estrategias de mitigación y adaptación climáticas más participativas, como la cogestión adaptativa o la Plan Espacial de Gestión inclusiva, con el fin de abordar la incertidumbre y conectar el conocimiento con compromisos que ofrecen y desarrollar alternativas para aumentar la resiliencia y la capacidad de adaptación del sector pesquero a escalas socioecológicas y socioeconómicas. (iii) Las capturas nominales de atún han ido disminuyendo con el tiempo en Mozambique, independientemente de si los peces son capturados por flotas industriales o pescadores en pequeña escala. La competencia entre las flotas industriales y los pescadores en pequeña escala para maximizar las capturas y los beneficios de las especies de túnidos de alto valor comercial, como el rabil, el listado y el patudo hayan contribuido, muy probablemente, a generar esta tendencia decreciente, ya que que los mismos stocks se capturan en diferentes regiones del océano Índico occidental (costa y alta mar) y por todo tipo de artes durante la migración estacional y espacial de las tres especies de túnidos tropicales. La existencia de tal interacción entre flotas industriales y pescadores locales a pequeña escala y la tendencia decreciente de los stocks tiene mayores consecuencias sobre los pescadores locales dada su mayor vulnerabilidad. Por lo tanto, es importante fortalecer la aplicación de la separación legal ya existente de las áreas de extracción entre la pesca artesanal e industrial. La costa norte de Mozambique depende más directamente de la pesca del atún, ya que hay un mayor número de pescadores involucrados en el segmento extractivo así como el trabajadores asociados al sector extractivo de la pesca. Por lo tanto, facilitar y promover los desembarques, los transbordos de atún y el procesamiento de la captura secundaria en Mozambique mediante políticas y gobernanzas más sólidas, probablemente mejorarán los ingresos sociales y económicos tanto de la pequeña escala como de la pesquería industrial en el país. Es importante evitar la explotación excesiva del atún en las aguas nacionales de Mozambique y al mismo tiempo establecer acuerdos de pesca que apoyen el desarrollo socioeconómico del país. Los futuros acuerdos deberían ser socialmente justos, viable ecológicamente y estar respaldados por un buen asesoramiento de gestión sobre la sostenibilidad de las tasas de explotación. Aunque las interacciones socioecológicas y económicas entre las flotas atuneras tropicales se analizaron a partir de las percepciones de los pescadores de las aguas costeras de Mozambique, la investigación adoptó un enfoque integrador para entender cuáles son los efectos de compartir recursos de gran valor económico, como los túnidos tropicales entre distintos tipos de pesquerías, prestando especial atención al escalón más vulnerable de la cadena, es decir, los pescadores artesanales locales. Por lo tanto, los resultados pueden contribuir a aumentar la conciencia de todos los interesados, como pescadores, administradores, compañías petroleras, tomadores de decisiones, entre otros, para abordar políticas y gobernabilidades hacia metas sostenibles.

Introduction

In the Western Indian Ocean (WIO), the Mozambique Channel (MZC) is located between African continent in the west and Madagascar Island in the East side, at latitudes between ~10ºS (Cape Amber in northern tip of Madagascar) and ~26ºS in south (Swart et al., 2010). The MCZ reaches ~3000 m in depth with a length of ~1600 km and narrow continental shelves on the Mozambican and Madagascan side (~430 km width) and wider (~1000 km) about 20ºS (de Ruijter et al., 2006) (Swart et al., 2010). The area is a highly dynamic marine ecosystem with complex oceanographic processes, such as strong water masses circulation and biophysical interactions (Tew-Kai and Marsac, 2010; Swart et al., 2010; Potier et al., 2014). These oceanographic processes are characterized with complex mechanisms of water mass circulation, such as the suggested possible dilution and mixing among the northward currents (e. g.: cold North Atlantic Deep Water – NADW and Antarctic Intermediate Water - AAIW), southward currents (e.g.: Read Sea Water - RSW and North Indian Deep Water – NIDW) and South Equatorial Currents (SEC) around the Comorian basin (e.g.: Ullgrenet al., 2012; Collins et al., 2016; Charles et al., 2020) (see Figure S1, Supplementary material [Supp.] A). Furthermore, there are effects generated by the cyclone and anti-cyclone eddies generated in northern area of MZC, carrying salty and warm upper layer waters fed by south equatorial current circulating southward, and merging with Agulhas intermediate water currents in southmost of the channel (de Ruijter et al., 2002; Ternon et al., 2014). Also, the existence of warm water (SST ~28ºC - 30ºC) is often related to tropical cyclone formation and storm intensification (Suzuki et al., 2004; Matyas, 2015), promoting high evaporation and contributing to increased precipitation, turbulence and mixing of water masses in the region. The cyclonic and anti-cyclonic eddies features, their interactions with continental shelf, and the effects of water masses mixing, enhance productivity along the Channel, attracting top large predators to aggregate in frontal and divergence zones of the eddies, as well as coastal productivity zones (Tew-Kai and Marsac, 2010; Potier et al., 2014). Also, African rivers discharge (e.g.: Mozambican rivers - Rovuma, Lurrio, Licungo and Zambezi; Madagascar - Betsiboka, Mahajamba, Mamambolo, Sofia, and Maeverano) contribute to nutrient supply in the area, enhancing productivity in the MZC with direct effects on the trophic levels (Omta et al., 2009; José et al., 2014). The oceanographic conditions, productivity, and efficiency of energy transfer enabled by short food chains (Chassot et al., 2019), make the northern part of MZC an attractive aggregation site for feeding and spawning of tropical tuna, among other fisheries resources (Chassot et al., 2019).

The environmental oceanographic instability in the MZC (Swart et al., 2010; de Ruijter et al., 2006; Matyas, 2015) seems to induce fluctuations of tropical tuna fisheries in the area, both in terms of interannual and seasonal variability. Also, tropical tuna stocks in the MZC have been targeted through competitive multi-interactions at the same fishing ground (Kleiber, 1991) among industrial fleets (e.g.: purse seine, longline, bait boat, pole and line, and trawling) (POSEIDON et al., 2014; Lecomte et al., 2017b), as well as interaction between industrial and small-scale fisheries by fishing the same species of tuna at different fishing grounds (Kleiber, 1991; Hampton, 1991), i.e., industrial fleets caught tuna offshore while small-scale fishers extract tuna in inshore areas. The environmental fluctuations and fleet interactions influence the temporal variability of tuna catches observed in the MZC (IOTC, 2020b, Database). Tuna seiners have attracted more attention due to increasing expansion and investment on innovative fishing technologies since 1980s (Lopez et al., 2014; Lopez and Scott, 2014), and fishing tactics (e.g.: FADs - Fishing Aggregating Devices and FSC - Free Swimming Schools) to improve tuna catch rates (Fonteneau and Chassot, 2014; Torres-Irineo et al., 2014). Tropical tuna (*Katsuwonus pelamis* (Linnaeus, 1758; skipjack tuna - SKJ) *Thunnus albacares* (Bonnaterre, 1788; yellowfin tuna - YFT) and *Thunnus obesus* (Lowe, 1839**;**

bigeye tuna - BET) are mainly targeted by European (e.g.: Spain, France) (Otterlei, 2011; Lecomte et al., 2017b; Augustave, 2018), and other regional purse seine fleets (e.g. Seychelles and Mauritius) (POSEIDON et al., 2014; Lecomte et al., 2017b), through fishing partner agreements (FPA). Despite the associated fisheries statistics uncertainty, it is believed that small-scale fisheries (SSF) catch~20 thousand tonnes of tuna and tuna-like species per year in the area, while the annual average catch export to can and sashimi markets by seasonal high sea fishing fleets is more than 20 thousand tonnes (Chassot et al., 2019). Along the MZC, SSF use a variety of fishing gears in coastal waters, such as small seines, gillnets, pole and lines, and hand lines, among others (POSEIDON et al., 2014; Lecomte et al., 2017b; Chassot et al., 2019). Stock assessments for the three main tropical tuna species in the Indian Ocean (IOTC, 2020b) suggest that the fishing impacts of the different fishing fleets may be different and determined that, currently, yellowfin tuna is overfished and subject to overfishing, while bigeye and skipjack are subject to overfishing and not subject to overfishing respectively (both species are not overfished).

The socioecological systems (the interface between human and the environment) and the socioeconomic role of the Mozambique Channel place the nations within the area in a potential emerging large blue economy (Andriamahefazafy and Kull, 2019; Obura et al., 2019). Socioecologically, the MZC coastal area is characterized by productive ecosystems such as mangroves (nursery grounds for fish and crustacean species), seagrass (used for feeding and reproduction of many marine species), coral reef producing calcium carbon, coral reef fish, sand banks and edge among other marine ecosystems (Richmond, 2002; Obura et al., 2019), all of them tightly linked to the people and human services in the area. Socioeconomically, elements such as ecotourism jobs and incoming generations, fisheries exploitation for livelihoods and economic commodities, extraction of oil and gas are well known to greatly contribute to the gross domestic product (GDP) economy of the countries in the region (Andriamahefazafy and Kull, 2019; Chassot et al., 2019; Obura et al., 2019). Interestingly, industrial tuna fisheries, mainly undertaken by distant water fishing nations, are the third income provider in the MZC regional states blue economy after coastal and marine tourism, and exploitation of oil and gas (Andriamahefazafy and Kull, 2019). Among tuna fisheries, purse seine fleets play a significant role for the countries' economies around the MZC by contribution through the licenses and compensation fees paid under FPAs (Lecomte et al., 2017a;Lecomte et al., 2017b;Augustave, 2018), while social impacts of the industrial purse seine fleets are still less known in the African countries around MZC (e.g.: Comoros, Madagascar, Mozambique, and Tanzania), although in Mauritius and Seychelles jobs provisioning in referral chain from transshipment, processing, and canneries are well documented (e.g.: POSEIDON et al., 2014; Lecomte et al., 2017a). The major social role of the SSF in coastal states and islands is job provisioning and food security for local communities around the MZC (Lecomte et al., 2017a; Chassot et al., 2019), whereas incomings are provided through referral chain of middlemen and resellers or by commercial oriented fisheries (McGoodwin, 2001). The local fishers communities combine multi fleets, gears and techniques to catch tuna, due to their high commercial value and high competence (e.g.: Campling, 2012; Lecomte et al., 2017a), i.e., fisheries exploitation seems to be one of the main drivers for the declines in tuna catch since the 2000s in the MZC (IOTC, 2019a). Other stressors may be related to IUU-fishing and piracy, particularly between 2005 and 2011 (Chassot et al., 2012; Pillai, 2012). As SSF operate inshore due to fishing technology and other limitations (Damasio et al., 2015), they have been rarely affected by piracy and IUU-fishing (Benkenstein, 2013), but may fill or perceive the declining of tuna, because they compete for the same stocks targeted by industrial fleets in the high sea. Therefore, there is socio-ecological interactions among and within fishing sectors (Hampton, 1991; Kleiber, 1991; Leroy et al., 2016), and over pressing tuna catches to maximize economic profits and livelihood (Panayotou, 1982;

Allison et al., 2009; Pitcher and Lam, 2015), leading to stock and biological indicators fluctuations (e.g. individual size or weight reduction).

On the other hand, climate change has become a global concern because, in many cases, its impacts in marine ecosystems distress the structure of fisheries and other living resources, and affect the redistribution, aggregation, and reallocation of marine species (Perry et al., 2010), with potential consequences in fishing communities. The ocean climate stressor, including increased global warming, acidification, ocean deoxygenation, and rise in sea level (Gruber, 2011; Ramírez et al., 2017), will affect, among others, the net primary production and ocean circulation and will induce physicochemical and biological changes at many biological and ecological levels. As the northern MZC is the tropical region predicted to suffer ocean warming at fastest rate (Roxy et al., 2014; Popova et al., 2016), migratory tropical tuna may quickly respond these effects by shifting their geographical distribution and move towards deepest waters, and/or temperate and polar regions (e.g.: Barange et al., 2014; Monllor-Hurtado et al., 2017). Therefore, as other developing nations around the world, the MZC, a region highly dependent on fisheries, is classified as with low adaptive capacity and highly vulnerable to climate impacts, and their national economies may suffer hardship under climate change (Allison et al., 2009). Hence, effective science-based decision making and communication are needed to increase awareness of climate-related risk and support communities' resilience and adaptation. Fisheries management bodies capable of evaluating and predicting the response of marine ecosystems to climate change are required to adequately assess the threats and opportunities created by climate change and guarantee the resilience of local fishers' communities (Lindegren and Brander, 2018).

As the Intergovernmental Panel on Climate Change (IPCC) pathway predictions (IPCC, 2014), projected that the greenhouse gas emission scenarios will increase sea surface temperature significantly by the middle and the end of the 21st century, where the marine ecosystems structure and living organism composition will change, with special emphasis in regions with warmest predictions like the northern part of the MZC. For instance, the Representative Concentration Pathways (RCP) 2.6 and 8.5 for 2050 and 2100 and mean sea surface temperature (SST) have been projected as follows: (i) the RCP2.6 (optimistic) emission scenario assumes least change, with an increase in temperature of 1º C by 2050 and 2º C by 2100, with an increase of salinity in 0.5 PSU and 1 PSU, respectively. (ii) the RCP8.5 (worst) scenario presumes most severe changes with an increase in temperature of 1.5º C in 2050 and almost 3º C in 2100, and increasing of 1 PSU and 1.5 PSU units for the salinity, respectively (Meinshausen et al., 2011; IPCC, 2014). Because the SST is also a good proxy for other environmental variables in the marine environment, such as the oceanic currents circulation, rising in sea level anomalies, chlorophyll-a concentration, oxygen supply to the ocean interiors, mixed layer depth, change in salinity concentration, ocean acidification, and stratification of water mass (e.g.: Mann and Lazier, 2006; Rahmstorf, 2007; Gruber, 2011; Aral and Guan, 2016; Popova et al., 2016), increasing in SST could be assumed to shift the dynamic of marine ecosystems and fisheries resources. As the ecological role of the SST is to be one of the main factors to determine the suitable habitats for tropical tuna world-wide (e.g.: Barkley et al., 1978; Matsumoto et al., 1984; Schaefer, 2001; Zagaglia et al., 2004; Houssard et al., 2017; Lan et al., 2017), part of the research in this thesis is based on the use of temperature as a predictive variable to project changes of tuna distribution, accumulation, and displacement in marine habitats under climate change scenarios.

In this context, the sensitivity of tropical tuna in marine ecosystem like MZC to various stressor, such as unstable environment, fast climate changes (e.g.: Lehodey et al., 2011; Roxy et al., 2014; Hobday et al., 2016; Popova et al., 2016), and multi fleets fisheries interaction and exploitation (e.g.: Grafton, 2010; Leroy et al., 2016; Lecomte et al., 2017b), disturb and disperse tuna from fishable patches or hotspots, potentially producing undesirable consequences to the socio-economy of fishing communities and regional countries. Thus, stakeholders, e.g., fishers, nations around MZC, and tuna regional fisheries management organizations (t-RFMOs) need to continue improving and strengthening the conservation and management policies and governance toward sustainability or those leading to adaptive capacity under various stressors (e.g.: Allison et al., 2009; Dulvy et al., 2011; Hanna, 2011; Lindegren and Brander, 2018). The uncertainty and magnitude of fisheries and environmental impacts like industrial and artisanal fisheries and climate change, require engagement and synergies of all stakeholders and agencies to be prepared with resilience and mitigation plans of the undesired impacts to reduce the socio-economic vulnerability of fishing communities and regional countries in the MZC.

a. Scientific objectives

The general objective of this dissertation is to improve our knowledge on the key factors driving the dynamics of tropical tuna fisheries in the Mozambique Channel, through an integrated and holistic approach using fisheries (industrial purse seine and small-scale fisheries), environmental and socio-economic information. In particular, the main goals are to investigate which environmental variables can explain the preferred habitat of tuna fishing grounds, predict the future distribution of tuna under different climate change scenarios, and investigate and discuss the socio-ecological and socio-economic aspects of tuna fisheries in Mozambique, with particular interest on the interactions between industrial purse seine fleets and local small-scale fisheries. The outcomes of the research are expected to be important for the correct conservation and management of shared stocks like tropical tuna, exploited for commercial and food security purposes in the region, and with the idea of contributing to address local and international policies and governance that guarantee the ecological, social and economic sustainability of the fisher's communities and nations.

In order to investigate the general aim, specific research objectives have been defined and summarized as follows:

1. Investigate the relationships between environmental factors and tuna catches caught by purse seiners around FADs and FSC in the MZC, to better understand their spatio-temporal dynamics, as well as their preferred environmental conditions and fishing grounds.
2. Improve the understanding of tuna catches redistribution under different climate change scenarios in the Mozambique Channel. Given the ecological and socio-economic role of skipjack tuna in the region, investigate the potential distribution and adaptation of skipjack tuna fisheries as a response to moderate and severe future scenarios of climate change by 2050 and 2100.
3. Quantify and describe the socio-ecological and socio-economic interactions and impacts of industrial fisheries on the SSFs sectors in coastal waters of Mozambique. As the tropical tuna stocks are shared by many fleets, even in distinct fishing grounds, it is necessary to investigate the multi-layer effects of the different fleets on both target stocks and the vulnerable local small-scale fisheries.

These objectives share a practical goal as they aim to provide scientific knowledge on the environmental and anthropogenic impacts on tropical tuna, useful for fisheries management and assess the socio-economic consequences on the fishers' communities from Mozambique and the surrounding countries. Furthermore, another outcome of this dissertation is to prioritize future research on climate change resilience and reduce the socio-ecological impacts on the region.

b. **Structure of the thesis**

The nature of this work and the divergence of questions and methodologies addressed during this thesis have led to present different research topics separately in different chapters. Each chapter is therefore presented as an individual scientific paper, with its own introduction, methodologies, results, discussion, and conclusions. Because of that, some redundant information has been unavoidably included in the introduction and material and methods sections of some chapters.

Background and Objectives

This is an introductory section summarizing information about the study area (Mozambique Channel), scientific knowledge relating oceanographic environmental effects on tuna distribution, aggregation, reallocation, and the potential impacts of climate change. Also, this section provides information on the different climate change scenarios, how they are estimated by international agencies and what are the most significant predicted consequences on both the environment and the human dimensions. Similarly, basic information on the main aspects of tuna fisheries in the region, their importance for the local and distant nation fisheries as well as some details on their dynamics and interactions is provided.

Chapter 1: Modelling seasonal environmental preferences of tropical tuna purse seine fisheries in the Mozambique Channel

Chapter 1 investigates the mechanisms driving tropical tuna fisheries into specific environmental habitats using fisheries dependent data and GAM (Generalized Additive Model) methods. The study explores the environmental preferences of the different fishing tactics used by industrial purse seiners (FADs and FSC), including spatial-temporal terms, oceanographic factors, and biological variables.

Chapter 2: Modelling the impacts of climate change on skipjack tuna (Katsuwonus pelamis) in the Mozambique Channel

Chapter 2 is dedicated to project the shifting of skipjack tuna under both the optimistic (RCP2.6) and pessimistic (RCP8.5) climate change scenarios by the middle (2050) and the end of the century (2100). Displacement of skipjack tuna catches, i.e., spatial-temporal reduction and reallocation of catches from current to new fishable hotspots were respectively forecasted under the inevitable climate impacts. The methodology acquired and applied in chapter 1 was further developed and extended for the main tropical tuna species, skipjack, using fisheries data, GAM techniques, and official climate change future scenarios. This chapter, also discusses the magnitude of uncertainty and impacts of climate change as well as the adaptive capacity of fishing communities and nations to reduce vulnerability, and improve resilience and mitigation of climate impacts.

Chapter 3: Socio-ecological and economic aspects of tropical tuna fisheries in the Mozambique Channel - Insight from Mozambique

Chapter 3 reviews, describes and analyzes the socio-ecological interactions and socio-economic aspects of tropical tuna fisheries in Mozambique. It provides insights of the industrial purse seiners operating in the high seas and the small-scale fisheries competing for tropical tuna in the Mozambican economic exclusive zone. The chapter explores the available literature, and commercial and logbook fisheries data, combined with dedicated data collection through the use of interviews with local fishers (‘Traditional Ecological Knowledge (TEK)’) to examine perceptions of tuna catch trends, interactions between fleets, and socio-economic aspects of the fisheries in the area. The socio-economic and ecological implications of the interactions on tuna fisheries were discussed, with special emphasis on the small-scale fisheries. Some conservation and management measures were discussed as well.

Finally, a section including a general discussion, potential future lines of investigations and conclusions is presented in the light of the main findings of this dissertation.

Chapter 1: Modelling seasonal environmental preferences of tropical tuna purse seine fisheries in the Mozambique Channel

1.1. Abstract

The spatial-temporal environmental preferences and catch aggregation of tropical tuna from purse seine fishery in the Mozambique Channel (MZC) have barely been investigated. In this study, tuna catch volume from Fish Aggregating Devices (FADs) and Free-Swimming Schools (FSC), collected by Spanish fishing logbooks during 2003-2013, were modelled separately as a function of a set of oceanographic variables (sea surface temperature, sea surface height, geostrophic currents, salinity, and chlorophyll-a) using Generalized Additive Models (GAMs). Temporal variables (natural day, month and year), and spatial variables (latitude and longitude) were included in the models to account for the spatio-temporal structure of dynamic catch of tropical tuna volume gathering. Oceanographic, temporal and spatial effects on aggregated catches differed between fishing modes, even though some common aspects appeared along the area and the period of study. Fishable patches of tuna catch accumulation were explained by sea surface temperature, productivity, sea surface height, geostrophic currents, and apart from the spatio-temporal variables interactions. Although the models predicted slight differences for tuna fishing spots preferences, both fishing modes partially overlapped. Goodness of fit for selected variables showed that models were able to predict tuna catches assembled patterns in the MZC reasonably well. These results highlight a connection between the biophysical state of the oceans and purse seine tuna catches in the MZC, and ultimately may contribute to the scientific advice for the appropriate management and conservation of the exploited resources by purse seine fleets in the area of MZC.

Keywords: Mozambique Channel, tuna catch, environmental preferences, GAM, purse seine

1.2. Introduction

The tunas are one of the most ecological and socio-economic valuable fisheries in the Indian Ocean, managed by The Indian Ocean Tuna Commission (IOTC). The three tropical tuna species, skipjack (Katsuwonus pelamis), yellowfin (Thunnus albacares) and bigeye (Thunnus obesus), together contribute more than half of the total Indian Ocean tuna catch (Lecomte et al., 2017a), and are the target species of many industrial and small-scale fisheries (Lecomte et al., 2017b; Chassot et al., 2019) caught by both coastal countries and distant fishing nations in the Indian Ocean (Havice and Reed, 2012; Lecomte et al., 2017b). Industrial purse seiners and longliners flagged as EU-France, EU-Spain, and Seychelles reported 34% of total catches of these species from an overall ~$1,050 million tonnes in 2019 (IOTC, 2020).

In the Western Indian Ocean (WIO), the Mozambique Channel (MZC) is a region where tropical tunas are mainly fished by European purse seine vessels from at least the 1980s and by longliners from 1850sand small-scale fisheries have been seeking tuna species throughout history (Miyake et al., 2004). Tuna schools are harvested by European purse seine fleets through two major fishing strategies that result in different species and size composition of the catch, i.e., tuna schools associated with Fish Aggregated Devices (FADs) and on Free Swimming Schools (FSC) (Delgado et al., 2008; Guillotreau et al., 2011; Dagorn et al., 2013; Fonteneau and Chassot, 2014; Torres-Irineo et al., 2014; Chassot et al.,2015). Sets on FADs are mostly composed with skipjack and juveniles of yellowfin and bigeye tuna, while sets on FSC targeted large adult yellowfin and bigeye tuna (Dagorn et al., 2013; Fonteneau and Chassot, 2014). Although large and small-scale fisheries operate in different fishing grounds, interactions between fleet catches of the three main tropical tuna species are common in MZC (POSEIDON et al., 2014; Lecomte et al., 2017b), leading to fishing pressure on tuna stocks.

Tropical tuna fisheries are the major source of economic profits and job provisioning in different segments of production chain (e.g.: extractive fishing, transhipment, fish processing, canning, and trading) in nations around MZC (Campling, 2012; Lecomte et al., 2017b). Therefore, while fishing activities on tropical tunas in developing coastal states, and, in particular, in MZC, contribute to the country's economy growth and supports social livelihood and food security (Obura et al., 2017), they are also the stressors affecting the catch of tropical tuna and related species due to high catch volume of tuna by various fishing communities (Lecomte et al., 2017b; Chassot et al., 2019).

Availability of tuna schools in the MZC are also often influenced by environmental conditions. Several authors have investigated the effect of environmental effects on tuna distribution (e.g. Fraile et al., 2010; Lan et al., 2017; Maunder et al., 2017), and catch aggregation elsewhere (e.g.:Yen et al., 2016; Lopez et al., 2017; Marsac, 2017) with few studies including the MZC (e.g.:Tew-Kai and Marsac, 2010; Dueri et al., 2014; Marsac, 2017). The oceanographic variables that have been most frequently linked to tuna populations (Song et al., 2009; Fraile et al., 2010; Lan et al., 2017) and other large pelagic species (Maravelias and Reid, 1997; Murase et al., 2009), included sea surface temperature, chlorophyll, sea level anomalies, salinity, sea surface currents, depth, and the space-time scale (Table 1.1). Effects of these physical-biological conditions in the oceans plays a significant role in influencing the spatio-temporal distribution and abundance of tropical tuna species. Furthermore, the increasing development of FADs purse seine fishing mode of the European fleets in the MZC is also influenced by environmental conditions. This makes the investigation of the dynamics of fish species and catch aggregation in relation to their marine environments of key importance which could contribute to providing guidelines for fisheries management and conservation measures in the Mozambique Channel.

Analysis of the effect of the physical-biological oceanographic variables on the distribution and catch density of tuna revealed seasonal change in pelagic fish distributions including tuna in the MZC. For example, during austral winter (March-June), tuna schools seem to peak in MZC (Kaplan et al., 2014; Obura et al., 2018), attracting purse seiners to fish in northern regions of the channel (Davies et al., 2014). The three main tropical tuna species seasonally fished by purse seines in the MZC, are Katsuwonus pelamis, Thunnus albacares, and Thunnus obesus (Campling, 2012; Kaplan et al., 2014).

Approaches and methods applied to infer the relationship of large pelagic species with specific oceanographic conditions are diverse (e.g.: APECOSM-E, GLM, MaxEnt, randomForest, MARSS). However, generalized additive models (GAM, Wood, 2006), have been recognized as powerful tools to investigate these effects in detail (e. g.: Maravelias, 2001; Murase et al., 2009; Fraile et al., 2010; Lan et al., 2017; Lopez et al., 2017), because of their flexibility to conduct robust regressions and the ability to model non-linear relationships through non-parametric splines (Hastie and Tibshirani, 1990).

There are limited studies in the MZC linking environmental conditions with fish catch accumulation as well as a scarcity of GAM application to investigate the concentrations of tuna catch in the study area. This limitation is related to difficulties in obtaining coastal catch data for small-scale fisheries. Spanish purse seine logbooks provide detailed information on catches and effort of tropical tunas in the MZC for the two fishing modes, FADs and FSC. As Spanish purse seine tropical tuna catches represent an important percentage of total catches reported by the WIO this study assesses the relationship between environmental factors and tuna catch accumulation using data provided by purse seiners in the MZC. The study objectives are to: (i) reveal their temporal dynamics, and (ii) predict the catch spatial aggregation hotspots in relation to their preferred environmental conditions. As tuna and tuna like species in the study area are under IOTC management (IOTC, 2019), results of this work may help regional management fisheries organizations and decision-makers to improve conservation and management measures while also supporting coastal states around the MZC area wishing to develop commercial and domestic tuna fisheries.

Table 1.1- Review of the importance of the environmental, spatial, and temporal variables on the distribution of tuna. ACS- Acoustic survey BET-Bigeye tuna; BLS- AO-Atlantic Ocean; Chl-chlorophyll-a; D. Expl. - Deviance Explained; DP-depth in the ocean; GC-Geostrophic currents; IO-Indian Ocean; Lat- latitude; LL- longline; Lon- longitude; Mon- Month/Season; PO- Pacific Ocean; PS-purse seine; Sal-salinity; SKJ- Skipjack tuna; Sp-Species; SSH, Sea Surface Height; SST- Sea Surface Temperature; TPT-tropical tuna (BET, SKJ, YFT); WIO- Western Indian Ocean; Yr-year; YFT-Yellowfin tuna. TPO- tropical Pacific Ocean; AO-EQP equatorial Atlantic Pacific Ocean; WPO - Western Pacific Ocean.

Area	**Data Source**	**Physical-Biological, Temporal and Spatial Variables**													**Authors**
		SST	**Sal**	**GC**	**SSH**	**O2**	**Chl**	**Lat**	**Lon**	**Mon**	**Yr**	**DP**	**Sp**	**Dev. Expl.**	
AO, IO, PO	LL	x	x		x		x			x	x		SKJ	63.7	Arrizabalaga et al., 2015
AO, IO, PO	LL	x	x		x		x			x	x		YFT	50.2	Arrizabalaga et al., 2015
IO	LL	x		x			x	x		x		x	YFT	*	Dell et al., 2011
WIO	TR	x			x	x	x			x	x	x	SKJ	*	Davies et al., 2014
AO, IO	PS	x	x	x	x	x	x					x	SKJ	*	Druon et al., 2017
AO, IO, PO	LL	x	x		x		x	x	x	x			SKJ	62.4	Erauskin-Extramiana et al., 2019
WIO	PS						x	x	x	x		x	SKJ	40.7	Fraile et al., 2010
WIO	PS						x		x		x	x	YFT	40.3	Fraile et al., 2010
PO	PS/LL	x					x					x	BET	48.6	Houssard et al., 2017
PO	PS/LL	x					x					x	YFT	33.4	Houssard et al., 2017
TPO	LL	x			x		x						YFT	33.60	Lan et al., 2017
WIO	ACS	x	x	x	x		x	x	x				TPT	*	Lopez et al., 2017
WIO	ACS	x	x	x	x	x	x						TPT	*	Orúe et al., 2020b
AO	PS	x	x	x			x					x	YFT	93.0	Maury et al., 2001
IO	LL	x	x	x	x		x						BET	*	Songet al., 2009
WIO		x		x	x		x						TPT	*	Tew Kai and Marsac, 2010
AO-EQP	LL	x			x		x	x	x	x			YFT	50.73	Zagaglia et al., 2004
IO	LL	x			x		x	x	x	x			YFT	28.6	Rajapaksha et al., 2013
WPO	PS	x	x	x	x		x	x	x	x		x	SKJ	13	Yen et al., 2016

- Deviance explained not provided

1.3. Methodology

1.3.1. Study area

The Mozambique Channel (MZC), is located in the southwestern part of the Indian Ocean, with Mozambique in the west, Madagascar in the east and the Comoros archipelago in the north (Figure 1.1). MZC is a good natural laboratory for investigating species relationship with the environment, due to the complexity of the sea surface circulation, with anti-cyclone and cyclone meso-scale eddies dominating the system (Lutjeharms and Town, 2006; Tew-Kai and Marsac, 2010; Ternon et al., 2014; Ruijter et al., 2015). The current flow in the north of the MZC channel is fed by the warm South Equatorial Currents (SEC), which generate eddies in Comorian basin, propagating south-westward through the channel. In the south, the SEC eddies, merge with eddies generated in the south-east of Madagascar and move westward to form the merged eddies currents trapped by the cold Agulhas Currents (Lutjeharms and Town, 2006; Tew Kai and Marsac, 2009; Ternon et al., 2014) (Figure S2, Supp. A). These circulation patterns, and other oceanographic features like sea surface temperature, sea level anomalies, salinity, oceanic fronts, with coupled interactions with nutrient enrichments, and plankton concentrations, play significant role on the marine ecosystem food web, and the consequent aggregation of top predators like tuna (Tew Kai and Marsac, 2009; Tew Kai and Marsac, 2010; Ternon et al., 2014; Druon et al., 2017; Lopez et al., 2017).

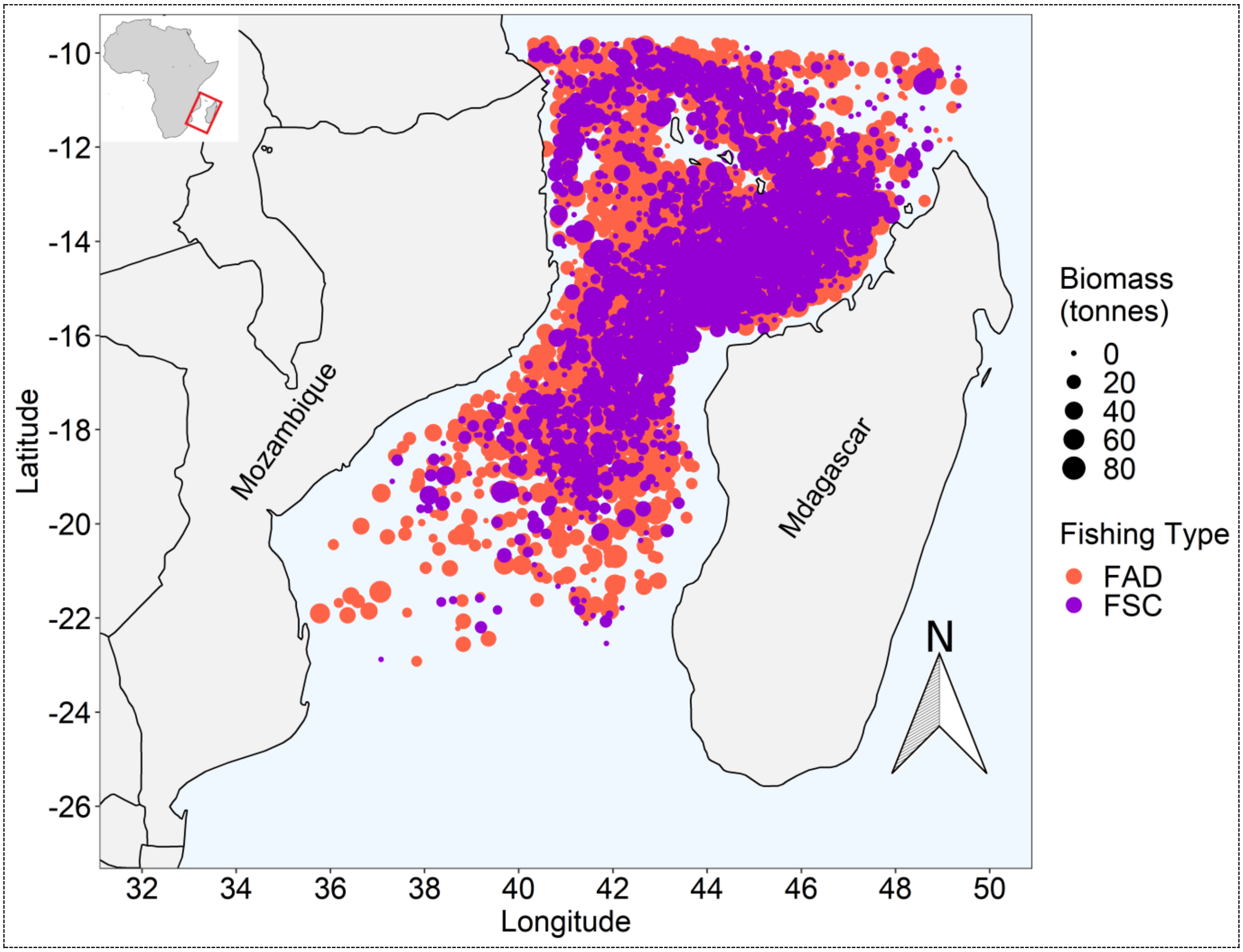


Figure 1.1 - Total catch distribution of tropical tuna species (Bigeye, Skipjack and Yellowfin tuna) in tonnes targeted by Spanish purse seine fleets in the Mozambique Channel for the period 2003 - 2013. Catches were monthly aggregated by 0.25º x 0.25º resolution. FSC - free-swimming schools and FAD - fish aggregation around devices.

1.3.2 Fishery Data

Scientific estimates of catches and effort data from the Spanish Oceanographic Institute (IEO) were used in the analysis. These estimates are obtained from the logbooks of the Spanish purse seine fleet in the Indian Ocean along the period of February 2003 –June 2013 after composition correction (Pallarés and Petit, 1998); and from detailed fleet data and port sampling. Catch and effort data from logbooks were detailed by set and consist of 3650 sets (7000 FAD and 6650 FSC). Catch proportion

(Figure S3, Spp. A) and information for Katsuwonus pelamis (skipjack), Thunnus albacares (yellowfin), and Thunnus obesus (bigeye) included size category in tonnes for each fishing type (FSC and FAD), fishing hours, date (year, month, and day of the fishing operation), and location (i.e., longitude and latitude). The data was spatially confined to the MZC in the western Indian Ocean, within latitudes of 8ºS to 30ºS and longitudes of 30ºE to 50ºE, and total catch was aggregated by fishing set per grid cells (Figure 1.1). Temporal window of catches was subset to the months between February to August which correspond to the fishing season in the MZC for the time series analysed.

Original logbook data from the tropical Spanish purse seine fishery requires the species composition in total catch of yellowfin, skipjack and bigeye to be corrected for each set (Pallarés and Petit, 1998). This procedure is carried out through a statistical established protocol designed by the Spanish Oceanographic Institute (IEO) and the Institute pour le Reserche and Developpment (IRD) with the program T3 (Tropical Tuna Treatment). The aim of T3 is to reduce the bias among the species composition in catches declared in logbooks, due to species misidentification, mainly among juveniles of bigeye, yellowfin and skipjack tunas. For each set, a weighting factor is applied assigning specific catches depending on the rectangle where the set was located in. Corrected catches are used as the scientific data presented by EU to IOTC secretariat.

1.3.3. Environmental Data

Environmental data for 2003-2013 in the MZC was obtained from the MyOcean-Copernicus EU consortium (marine.copernicus.eu) in netCDF format. Physical and biological environmental data were extracted for each fishing set location of the each date from netCDF files through loop function codes and are the following: sea surface temperature, sea surface temperature gradient derived as the decrease or increase in temperature for each pixel over an 7-day period, sea surface height, eddy kinetic energy (derived from altimetry), sea surface current velocity, heading-direction of the current sea surface, salinity, chlorophyll-a concentration, chlorophyll-a gradient derived as the increase or decrease of chlorophyll amount in each pixel over an 7-day period, and dissolved oxygen concentration (Table 1.2). Then, environmental variable data were merged with fisheries data by fishing set, (i.e., longitude and latitude, year, month, and day). The spatial and temporal resolution was 1/4° and daily, respectively. Besides oceanographic variables, spatial-temporal variables were included in the analysis to better isolate the effect of the environment and could be misinterpreted as abundance variables or even masking some other environmental processes not included in the model. These spatial-temporal variables were longitude, latitude, year, month, day, and natural day, i.e., from 1 to 365 days (Cortés-Avizanda et al., 2011).

Table 1.2 - Environmental, spatial and temporal variables used in the study

Variables	**Acronym Used**	**Unit**	**Spatial Resolution**	**Temporal Resolution**
Chlorophyll a concentration	CHL	$mg\ m^{-3}$	0.25º x0.25º	Daily
Chlorophyll Gradient concentration	CHLGD	$mg\ m^{-3}$	0.25º x0.25º	±7 days
Current Heading	HDG	degrees	0.25º x0.25º	Daily
Eddy Kinetic Energy	KE	$m^2\ s^{-2}$	0.25º x0.25º	Daily
Current Velocity	SSC	$m\ s^{-1}$	0.25º x0.25º	Daily
Sea Surface Height	SSH	m	0.25º x0.25º	Daily
Oxygen concentration	O_2	$mg\ l^{-1}$	0.25º x0.25º	Daily
Sea Surface Salinity	SSS	$g\ kg^{-1}$	0.25º x0.25º	Daily
Sea Surface Temperature	SST	ºC	0.25º x0.25º	Daily
Sea Surface Temperature Gradient	SSTGD	ºC	0.25º x0.25º	±7days
Latitude	Lat	degrees	0.25º x0.25º	Daily
Longitude	Long	degrees	0.25º x0.25º	Daily
Month	Month	-	0.25º x0.25º	Monthly
Natural Day (365 days per Year)	YearDay	-	0.25º x0.25º	Daily
Year (2003 -2013)	Year	-	0.25º x0.25º	Yearly

1.3.4. Data Analysis

For the purpose of this analysis, corrected individual species composition in catches was aggregated to define total catch by set (e.g.: Catch = BET + SKJ + YFT); where BET, SKJ, YFT are the catch of yellowfin, skipjack and bigeye, respectively. Due the differences in catch composition and sizes between the two types of sets (FADs or FSC) this aggregation makes sense to represent catch of tropical tunas as a group. For FAD sets, the effect of oceanographic variables impacts the aggregation of schools of skipjack, juveniles of bigeye and yellowfin while for FSC sets, catches of adult yellowfin predominate.

All the statistical analyses were conducted in the R software version 3.5.0 (R Core Team, 2018). Exploratory data analysis included a visual checking of the data through the cloud function in the lattice package (Sarkar, 2008) in order to have a general overview of the potential relationships of covariates and the response variable (i.e., tuna catch) in time and space. The relative effect of covariates on the dependent variable was also explored to gather information on the most important variables effecting tuna catch and reduce model complexity in further stages (Dell et al., 2011), using randomForest package (Liaw and Matthew, 2002).

Correlation among predictor covariates was tested using pairwise plot and Pearson rank correlation scores, and one covariate between covariates pairs with correlation coefficient $\geq +0.70$ and ≤ -0.70 was dropped from the variable selection process (Dormann et al., 2013), based on the relative importance test and the ecological expert knowledge and literature for the species (Zuur et al., 2009). A variance inflation factor analysis was also conducted as an additional measure to test collinearity using a threshold value of 3 (Zuur et al., 2009). Hence, the covariates natural day, oxygen concentration, and current velocity were dropped for further modelling phase due to collinearity and correlation with ecologically more important environmental variables.

Furthermore, boxplots were used to visualize and inspect positive catch distribution, detect and correct outliers. However, some authors (e.g.: Zagaglia et al., 2004; Cortés-Avizanda et al., 2011) suggest that there is no need for the prior assumption of normality and linearity required to fit GAM models. For this analysis normal, lognormal, and gamma distributions were fitted to the response data by fishing mode using the fitdistrplus package (Delignette-Muller and Dutang, 2015), to determine which distribution family should be best used for modelling. For the first step, normality was tested with original response data. Then, as statistic results and graphical inspection shown that the original data did not follow the normal distribution, data were transformed to logarithmic scale and model refitted to meet normality criteria (Underwood, 1997; Wood, 2006; Zuur et al., 2009). Assumption for good distribution model were based on lowest Akaike Information Criterion (AIC), Kolmogorov-Smirnov statistics and graphical inspection (Delignette-Muller and Dutang, 2015). However, for FSC, Kolmogorov-Smirnov statistics was relatively favourable to lognormal distribution, whereas AIC and graphical inspection were indicating the use of normal distribution for the logarithmic scale transformed response variable (set in the exploratory analysis in section 2.1), as the best distribution to fit the model.

In early stages of the modelling, daily set by set data for each fishing mode was used. However, because of the low performance of the models and the failure to detect the variance changes at this scale, data were monthly aggregated to 1/4º grid cell (such as sum for the catch and mean for the environmental variables). Details to create different scale grids and raster layers through the raster package can be found in Bivand et al. (2015) and grey literatures.

GAMs were established to examine the effects of environmental variables on the spatio-temporal tuna catch aggregation for each fishing mode (i.e., FADs and FSC). The logarithmic transformation of total catch (i.e., log(Catch+1)) was used as the dependent variable to reduce skewness and improve model performance (Wood, 2006). GAMs were fitted using a Gaussian family with identity link function using the gam function from the mgcv statistical package in R (Wood, 2006), following the recommendations for modelling continuous data (e.g: Wood, 2006; Zuur et al. 2009; Zuur et al., 2010), and the distribution tests as follows:

$$Y = \alpha + \sum_{j=1}^{n} f_j(x_j) + \varepsilon$$

where, Y is the response variable, α is a constant, f_j are regression coefficients or smoothing functions, x_j are measured values for predictor variables and ε is the residual. The best GAM for each fishing mode was obtained with a backward stepwise procedure (see details below), starting from an annotation as follows:

ln (Catch+1) ~ te(space-time, k= (50,6), d = c(2,1) + s(Ca, Cb, k = 20) +
s(Cc, k = 6) + … c(Cc, k = 6) + s(Cz, k=6) + *random*

where the function te forms the product from the marginal's terms of the space-time triple interactions, d is the dimension of each spline in the triple interaction which in our case is two for spatial components and one for temporal term. The s is the penalized spline smooth function, for the single interactions, and environmental covariates (C). All interactions were fitted by the tensor product smooth (ts), while the single covariates were fitted with cubic regression spline (cs) to model nonlinear relationships. The "cs" ensures that a regression spline with shrinkage is applied, a smoother can have zero degrees of freedom, and all smoothers with zero degrees of freedom can be dropped simultaneously from the model (Zuur et al., 2009); c specify cyclic cubic regression spline used to illustrate the cyclical behaviour of the sea surface currents direction denoted as heading (Wood, 2006), and the random effect account for inter-annual variability in fishing effort and fleet behaviour (Brodie et al 2015). Dimension, k, representing the maximum degrees of freedom for each smooth term, was set as k = 6 for the main effect, k=20 for the first order interaction

(Cardinale et al., 2009; Giannoulaki et al., 2013; Jones et al., 2014). The value of k=50 for spatial components in the space-time triple interaction was found after trial-and-error selection of k (Wikle et al., 2019), to avoid models overfitting, and to simplify the interpretation of the results.

Covariate selection was performed applying a backward stepwise elimination procedure based on the following criteria: (i) the approximate 95% confidence band for the smooth term included zero everywhere; (ii) Generalized Cross Validation (GCV) score drop when the term was dropped (Wood, 2001); and (iii) Akaike Information Criterion (AIC) score decreased when the term was deleted (Akaike, 1974). Final models with lowest GCV and AIC scores were selected.

The goodness-of-fit of the models was assessed by examining and considering diagnostics checks, the percent of deviance explained, lowest AIC and GCV scores, the graphical inspection of the residuals to access normality and homogeneity, and the straight linearity between fitted values and response (Hastie and Tibshirani, 1990; Wood, 2006a; Zuur et al., 2009). Furthermore, residual spatial autocorrelation was tested with the spline.correlog function from the ncf package (Bjørnstad et al., 2001).

Four temporal term candidates were tested (i.e., month as a factor, month as cubic spline, space-time triple interaction, and natural day). The default GCV was chosen as the best smooth selection parameter over the Restricted Maximum Likelihood (REML) and Marginal Likelihood (ML), as GVC select optimal smooth parameters (i.e., low prediction error as the sample size tend to infinite) (Wood, 2011).

Model validation was based on the k-fold cross validation, consisting of randomly split observations on k groups, which in this case k was set to 10 folds. The first fold was treated as a validation set, and the model was fitted on the remaining k − 1 folds (James et al., 2014). Then, root mean square error rate (RMSE) was computed as metric measure accuracy to evaluate model prediction on the held-out fold observation data. Also, similarity index between observed and predicted data was estimated (Warren et al., 2008), through niche Overlap function in the dismo package (Hijmans and Elith, 2017), and Pearson correlation test (r2) between predicted and observed catches were estimated through cor.test function in the base stats package (R Core Team, 2018).

1.4. Results

Table 1.3 summarizes the goodness-of-fit criteria and the statistics of the response variable distribution considered in our analysis as recommended for continuous data. The analysis showed that normal distribution of the logarithmic scale transformed response data were the best fit distributions for both FAD and FSC fishing mode data. Catch of about 197,078.30 tonnes of tropical tuna aggregated northward of MZC over the study period, accounted with 68% of the total catches for FADs, while for FSC was about 32% of total catches.

Table 1.3 - Statistics summary for testing the best fitted distribution to the data. AIC-Akaike Information Criterion; FAD-fishing around aggregating devices; FSC- free swimming schools; KSS- Kolmogorov-Smirnov statistic; Normal log(x+1) - refer to the response data transformed to logarithm scale. p-value of Kolmogorov-Smirnov statistic help to indicate that sample follow (p-value >0.05) or not (p-value<0.05) the normal distribution.

Data Model Fit	**FAD**			**FSC**		
Statistic	**AIC**	**KSS**	**p-value**	**AIC**	**KSS**	**p- value**
Normal	35424.03	0.1854	<0.0001	15718.31	0.2381	<0.0001
Gamma	31885.42	0.0557	<0.0001	13595.77	0.0699	<0.0001
Normal log(x+1)	9274.67	0.0212	0.1249	4325.83	0.0341	0.1238

Table 1.4 summarizes final spatio-temporal GAM models. Models with triple interactions were finally selected based on performance scores. Covariate selection differed between FAD and FSC fishing, although the space-time triple interaction was the most significant terms in both fishing

modes. The shapes of the functional forms for the selected covariates for both FAD and FSC models were plotted (Figure 1.2 and 1.4). Both FAD and FSC models displayed non-linear responses to the covariates. The predicted relative tuna catch assembled by fishing mode also exhibited different spatial distribution patterns in the area. The performance scores of the models, including deviance explained, AIC and GCV scores, effective degree of freedom (EDF) and variables significance can be found in Table 1.4.

Table 1.4 - Selected GAM models for seasonal and spatial catch distribution for tropical tuna species. All models were fitted with gaussian distribution with identity link. EDF: effective degree of freedom; FADs: fishing aggregating devices; FSC- fishing on free swimming schools; SSH - sea surface height; CHL - chlorophyll-a; SST - sea surface temperature; SSTGD- sea surface temperature gradient; SSS - sea surface salinity; CHLGD -: chlorophyll-a gradient; HDG - heading (sea surface currents direction); VEL - sea surface current velocity; KE - Kinetic energy; Long - Longitude in degree; Lat - Latitude in degree.

Parameters	**Model Fitted with Gaussian Family Identity Link**			
	FAD		**FSC**	
Adjusted R^2	0.20		0.27	
Dev. Explained. (%)	22.60		32.60	
AIC score	6790.28		3137.36	
GCV score	0.60		0.78	
n	2925		1217	
EDF	106.35		100.00	
Residual df.	2818.65		1124.93	
Covariates	***EDF***	***p-value***	***EDF***	***p-value***
CHL	-	-	4.78	<0.001
CHLGD	-	-	-	-
HDG	3.57	<0.001	-	-
KE	4.75	<0.001	-	-
MONTH	-	-	-	-
SSH	1.95	<0.01	3.35	<0.001
SSS	4.37	<0.01	4.39	<0.001
SST	-	-	-	-
SSTGD	-	-	-	-
VEL	-	-	-	-
Year			0.11	<0.001
Natural day	-	-	-	-
CHL x CHLGD	8.70	<0.05	-	-
SST x SSTGD	11.48	<0.001	12.42	<0.001
Long x Lat x Month	70.52	<0.001	73.95	<0.001

1.4.1. FAD Model

The final GAM for FADs explained 22.60% of the deviance with an adjusted R2 score of 0.20 (Table 1.4). The spatial correlograms showed non-significant residual autocorrelation, and model residual check displayed histograms close to the normal distributions, and the variance met homogeneity criteria (Figure S4, Supp. A). The selected variables were, ordered according to the variable significance (i.e., p-value): interactions longitude - latitude - month (Figure 1.2a), SST - SSTGD, CHL - CHLGD, single covariates such as KE, HDG, SSH, and SSS (Figure 1.2b and Table 1.4). The top panel in Figure 1.2a, shows that tuna catch was high along the Mozambique coast at the latitude 18ºS and 24ºS in February and early March. In late March up to May, tuna catch was more aggregated in west coast of Madagascar at latitude 12ºS and 17º S, and from June to August the catch was relatively accumulated in northern area of the MZC below 12 ºS. It seems that for the period of June to August, model suggest that purse seiners quit fishing in the Mozambique Channel.

Tuna catches revealed two distinct groups, i.e., schools with preference in waters where temperature changed by ±2ºC in a week period from 24ºC up to 28ºC, and waters above 29º where temperature changed between ±2ºC. Those waters were characterized by patches where chlorophyll concentration changed between ±0.2 mg Kg-1 in a week period. The shape of functional forms in the patches where tuna catch aggregated exhibits relative flattened trend with KE intensity, increasing in waters moving toward west-southward. Higher catch of tuna was related to salinity waters ranged between 32 gkg-1 to 34.5 gkg-1, where SSH elevation was below 0.6 m. Contour map from GAM, revealed two hotspots of tuna catch located in northern west tip of Madagascar between the latitude 12ºS and 16ºS (Figure 1.2b).

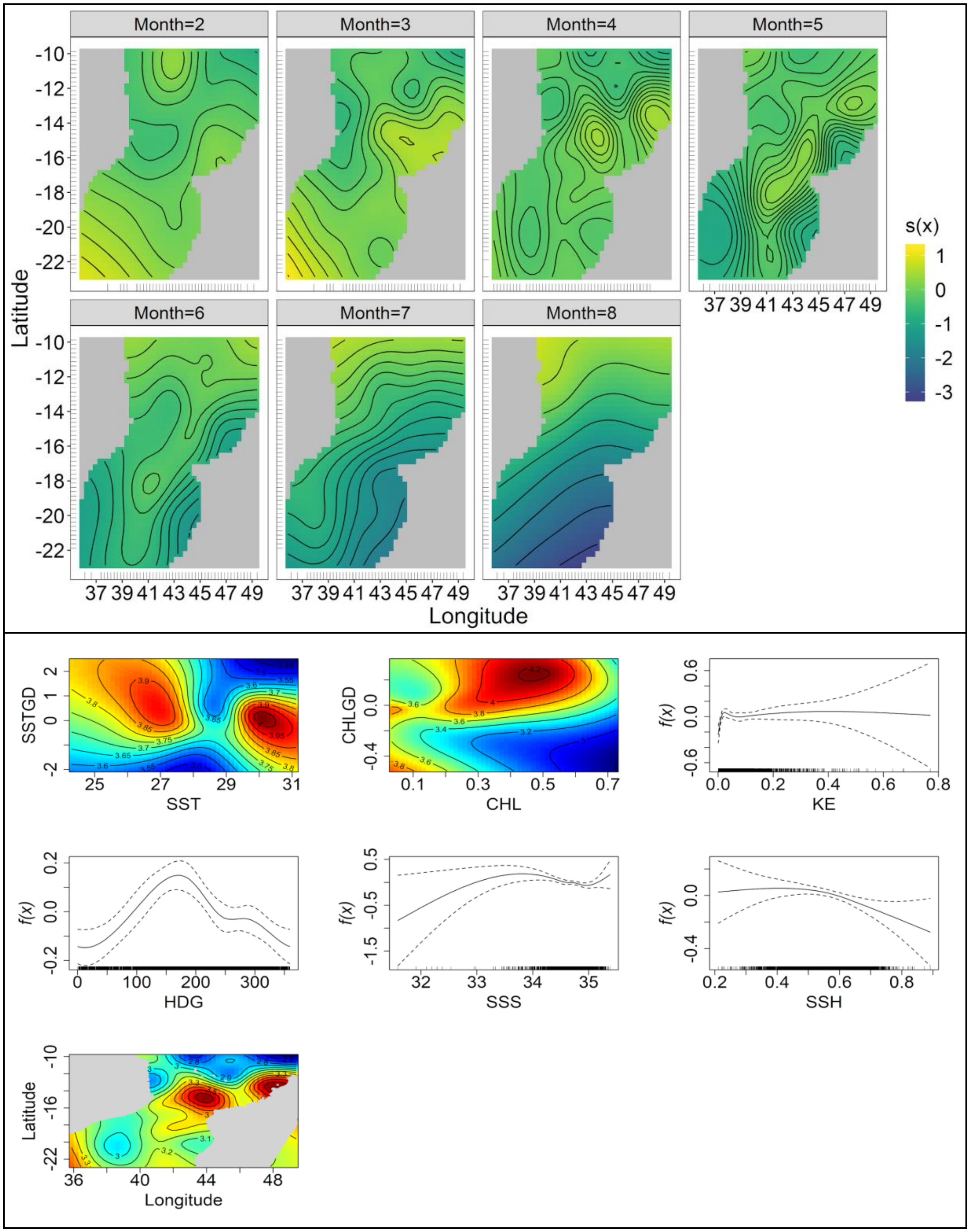


Figure 1.2 - Smoothed fits of covariates from GAM, modelling catch of tuna catches in FAD. Top panel is partial effect of the tri-dimensional interaction longitude x latitude x month in surface plot. Bottom panel are partial effect of the two-dimensional terms (SST x SSTGD, and CHL x CHLGD), partial effects of each covariate (Ke, HDG, SSH, and SSS) plotted as smoothed fits, and contour map of catches distribution. Tick marks on the x-axis are the observed data. The y-axis represents the smooth terms contribution to the model on the scale of linear predictors. y-axes, denoted as f(x), reflects the relative importance of predictor variable of the model. Dashed lines indicate the lower and upper 95% confidence bunds of the smooth plotted

Figure 1.3 displays predicted catch aggregated around FADs along the Mozambique Channel. The maps for the area of the Mozambique Channel illustrated that tuna catch density is high in northern Mozambique Channel, with the core observed in north-west coast of Madagascar Island at the longitude 42ºE to 47ºE, and latitude12ºS to 20ºS. GAM predicted tuna catch density decreased west-southward and west-northward along the Mozambique Channel, surrounding Mayotte and Comoros Island waters (Figure 1.3). Low catch density was expected at the latitude above 20ºS, falling to zero nearest Mozambique cost. There was no predicted catch at high latitudes above 23ºS in the study area. GAM predicted tuna catch aggregation in MZC similarly to the observed catch around FADs, i.e., RMSE was 0.09, Schoener similarity index "D" was about 0.90, and Pearson correlation test was about r2 =0.44.

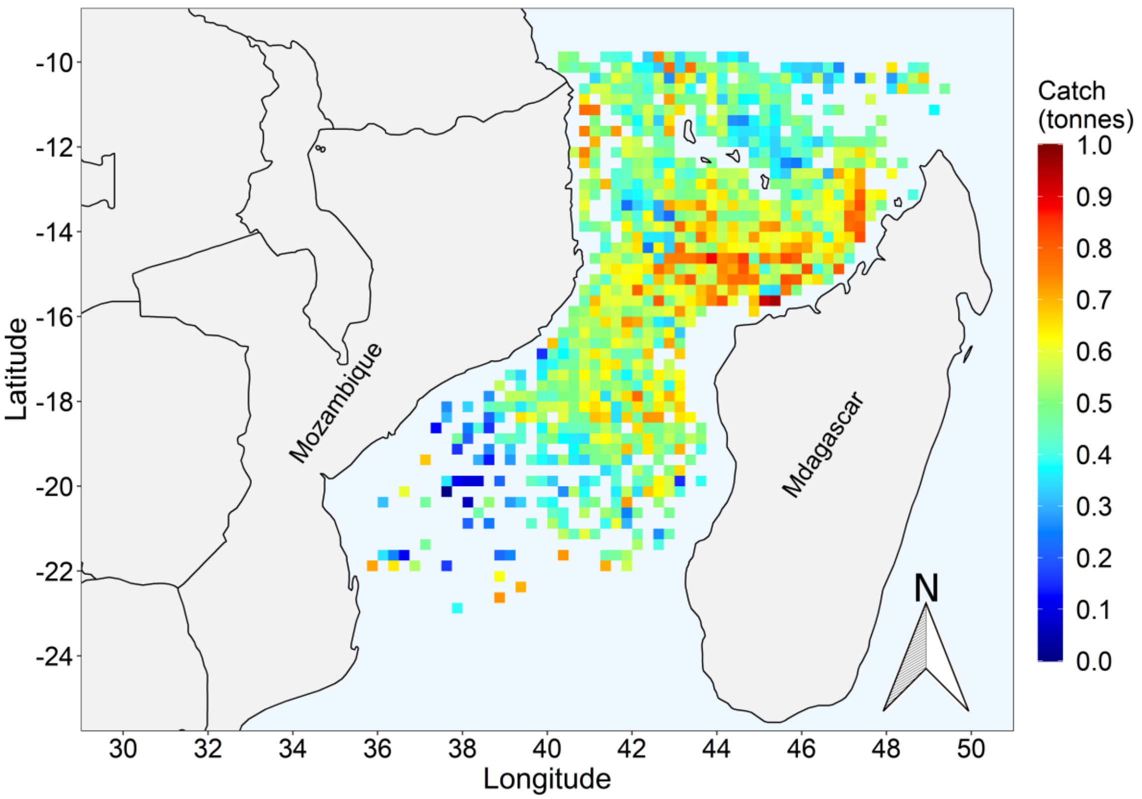


Figure 1.3 - Predicted spatial distribution of normalized tuna catch density caught in FADs fishing mode in the Mozambique Channel area. Data are tuna catch for the period 2003-2013, gridded by 0.25º x 0.25º spatial resolution, and transformed to natural logarithm scale for better performance in GAM modelling.

1.4.2 FSC Model

Final FSC model for the tuna catch explained 32.60% of the deviance with an adjusted R2 score of 0.27 (Table 1.4). The spatial correlograms displayed non-significant residual autocorrelation, and model residual check followed homogeneity criteria, and histogram close to the normal distributions (Figure S5, Supp. A). Covariates selected for the final model, in order of significance, were (Table 1.5, Figure 1.4): interactions longitude - latitude - month (Figure 1.4a), SST - SSTGD, single terms such as SSS, SSH, and CHL (Figure 1.4b). Figure 1.4a depicted that in February tuna catch density was located north of the Mozambique Channel. High catch was observed in April and May, and similarly to the FAD strategy, GAM detected that FSC seiners start to leave Mozambique Channel to other fishing ground between June and August. However, between June and August the records of catch were relatively high, the frequency of sets was very low, revealing departure time of seiners to other fishing patches (Figure 1.4a). Higher catch density was associated with waters of SST above 26ºC, where SSTGD was changing between ±1.5ºC in a week period (Figure 1.4b). In relation to salinity, tuna exhibited flattened trend at relatively low SSS water, and a peak in waters where salinity was around 34.5-35 g Kg-1. Furthermore, tuna catch was positively related with SSH values 0.4-0.6m, while in relation to the CHL, a relative decreasing trend with increasing chlorophyll-a concentration was found (Figure 1.4b). Contour map depicted fishing hotspots for FSC seiners at the west tip of Madagascar at the latitude 14ºS to 16ºS, another hotspot in northern part of the Channel, reaching Mozambique coast at the latitude below 12ºS (Figure 1.4b).

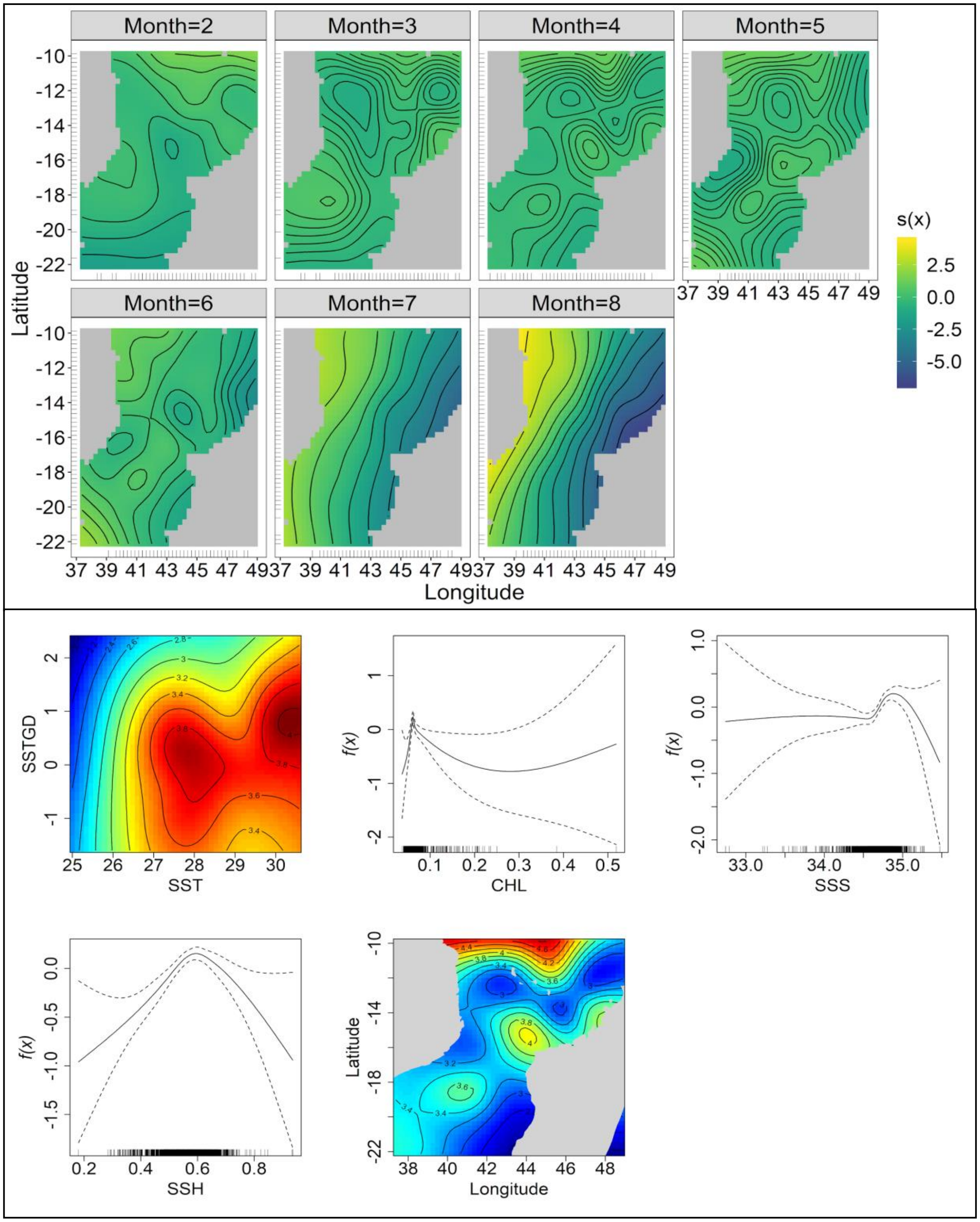


Figure 1. 4 - Smoothed fits of covariates from GAM, modelling catch of tuna catches in FSC. Top panel show partial effect of the tri-dimensional interaction longitude x latitude x month in surface plot. Bottom panel are partial effect of the two-dimensional terms (SST x SSTGD), partial effects of each covariate (SSS, SSH, and CHL) plotted as smoothed fits, and contour map of catches distribution. Tick marks on the x-axis are the observed data. The y-axis represents the smooth terms contribution to the model on the scale of linear predictors. y-axes, denoted as f(x), reflects the relative importance of predictor variable of the model. Dashed lines indicate the lower and upper 95% confidence bunds of the smooth plotted.

Figure 1.5 shows tuna catch prediction for FSC in the Mozambique Channel. The sketched maps show that the expected tuna catch density was high in northern of Mozambique Channel, with core in north-west coast of Madagascar Island at the longitude 40ºE to 46ºE, and latitude10ºS to 20ºS. From the core, GAM predicted high catch density around northern part of Mayotte and Comoros Island waters (Figure 1.5), and southward along the Madagascar coast. Low catch density was predicted at the Mozambique coast, and there was no expected catch accumulated above 22ºS. GAM predicted catch accumulation in the MZC similarly to the observed catch from FAD set types, with RMSE accuracy of 0.09, Schoener "D" similarity index was about 0.89, with Pearson correlation test r2 = 0.52.

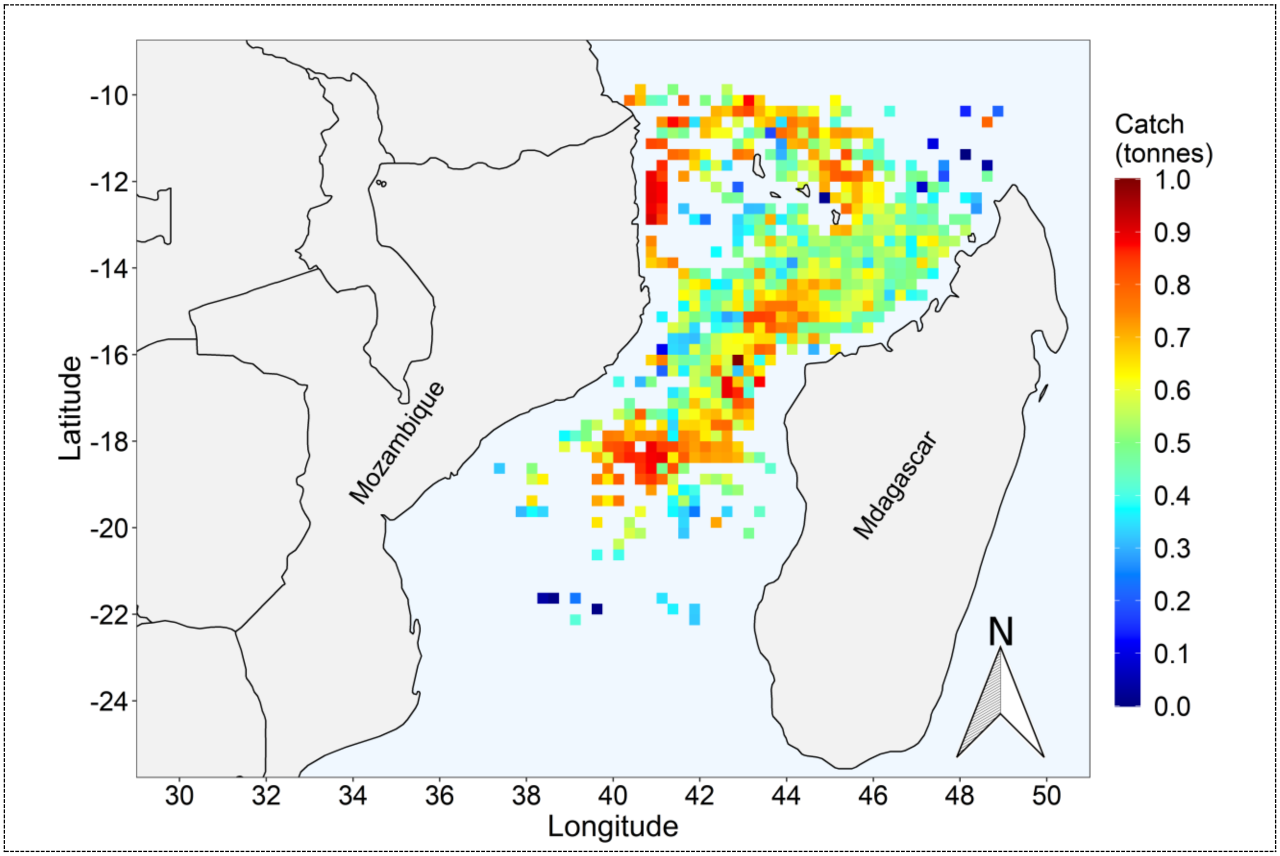


Figure 1.5 - Predicted spatial distribution of normalized tuna catch density caught in FSC fishing mode in the Mozambique Channel area. Data are tuna catch for the period 2003-2013, gridded by 0.25º x 0.25º spatial resolution, and transformed to natural logarithm scale for better performance in GAM modelling

Difference between FAD and FSC predicted catch is shown in Figure 1.6. FAD associated catch dominates the north-west coast of Madagascar, whereas, values of FSC were much high mostly in the northern of the Mayotte and Comoros Islands, crossing anticlockwise to the Mozambique coast, and between latitude 17ºS and 19ºS. Areas with no difference on catches between the two fishing modes, were randomly predicted, covering many fishing grids along the Mozambique Channel. However, the variable selected by GAM differed between the two fishing modes, there was partial overlapped fishing ground predicted for both fishing strategy.

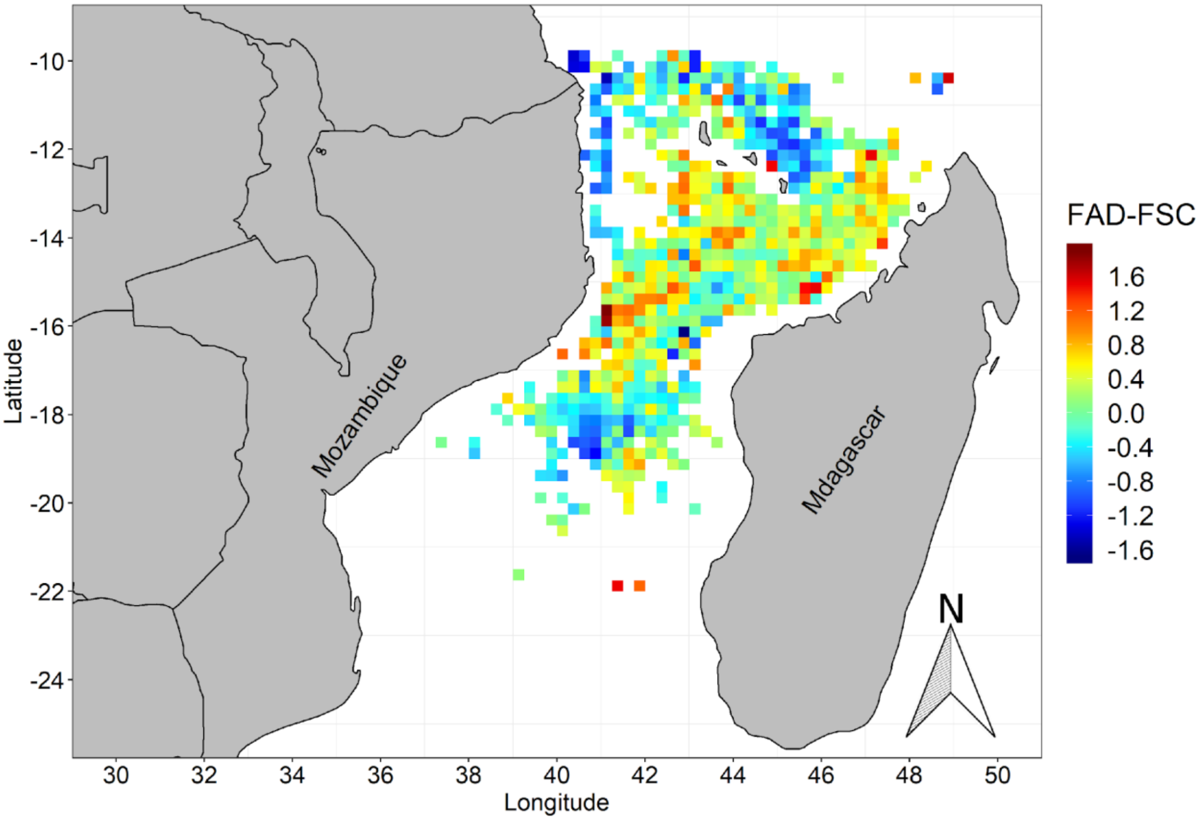


Figure 1.6 - Map displaying the difference between normalized catch predicted from FAD and FSC in the Mozambique Channel for the period 2003 to 2013. Colours rank scores below zero indicate regions where the catch of FSC was expected high, colours rank scores above zero correspond to the areas for high catch density of FAD (green yellow-dark red grids), and areas indicated no difference (light green colours) on expected catch density between the two-fishing strategy was record zero score.

1.5. Discussion

This study presents the evidence for different relationships between tropical tuna catch accumulation and environmental data for tuna catch associated with FADs and FSC in the MZC. These relationships have been identified through GAMs, confirming that additive models are adequate to model oceanographic and catch data. The best fit of the GAM model for FAD explained 22.60% of the deviance and R2 = 0.20, whereas for FSC the deviance explained was about 32.60% and R2 = 0.27. This difference could be related to marked environmental preferences for each group, especially FSC tuna (Maury et al., 2001; Druon et al., 2017). It is widely recognized that FSC tuna are usually more strongly related to certain environmental conditions that shape the availability of schools in the area (Maury et al., 2001; Fonteneau et al., 2008; Druon et al., 2017). On the other hand, the known effects of FADs on changes in tuna species behavior, interactions with other species, and tuna schools driven to inappropriate habitats in marine ecosystem (Hallier and Gaertner, 2008), could explain the lower deviance comparable to FSC. GAM were evaluated through cross-validation, with better model accuracy RMSE ~ 9% (James et al., 2014; Wikle et al., 2019;), for both FAD and FSC. Schoener similarity index “D”, between predicted and observed catch aggregation was 0.91 for FAD and 0.89 for FSC, showing that GAM was capable to predict tuna catch aggregation in MZC (Warren et al., 2008), and Pearson correlation was reasonably good for FAD and FSC close to 44%, and 52% respectively. (The spatial correlograms showed non-significant residual autocorrelation, suggesting that models are adequately capturing spatial residual and variance patterns (Bjørnstad et al., 2001). Furthermore, goodness-of-fit of the models met the basic criteria through residual checking (Wood, 2006; Zuur et al., 2009).

Regarding the temporal component, in both fishing type models, GAM revealed certain seasonality of tuna catch in the Mozambique Channel. This is also confirmed by the presence of purse seiners in the area (Campling, 2012; Davies et al., 2014; Kaplan et al., 2014) where fleets start fishing in February-March, up to June, with the highest activity seen around April-May (Figure 1.2a and 4a). It seems that purse seiners quit fishing in the MZC in late June, following tuna migration, probably to the Somali coast during summer upwelling monsoon, and other fishing habitats in Indian Ocean (Tew-Kai and Marsac, 2010; Campling, 2012; Kaplan et al., 2014; Ternon et al., 2014; Orúe et al., 2020). The seasonality of tuna catch could be related to the variation of the physical driving force of the primary production (Tew-Kai and Marsac, 2009; Tew-Kai and Marsac, 2010; José et al., 2014), and the subsequent shift of prey density (Dell et al., 2011), influenced by the seasonal and interannual dynamics of the environment.

Relating to the spatial component, GAMs have also been proven to be powerful tools to account for environmental changes in the spatial domain (e.g:. Maravelias, 2001; Mourato et al., 2008; Murase et al., 2009; Brodie et al., 2015; Lan et al., 2017). For tuna catch around FADs, GAM results suggest that tuna catch accumulated weekly in water temperature changes by ±2º, however, two distinct groups of tuna in relation to SST preference were observed. One group preferred habitat between 25ºC to 27ºC whereas a second school prefers waters about 29ºC to 31ºC (Figure 1.2b). These findings support earlier studies which documented that tuna inhabit warm pools and may accumulated in cold water fronts with prey enrichments for feeding (Fiedler and Bernard, 1987; Watson et al., 2018). The preferred range of SST is between 25ºC - ,31Cº found in FAD models are the typical values shown by tropical tuna in the Indian Ocean (Rajapaksha et al., 2013; Arrizabalaga et al., 2015; Druon et al., 2017; Duffy et al., 2017). The current research found tuna catch around FADs was associated with patches where CHL concentrations changes around ±0.4 mg. l-1 over a one week period. Possibly, sea surface currents (kinetic energy and heading) played significant role on tuna catch associated with FADs. The effect of oceanic currents on the redistribution of plankton, micronekton, heat, oxygen and nutrients fluxes has been widely recognized (Fu, 1986; DiMarco et al., 2002; Bryden and Beal, 2001; Anilkumar et al., 2006; José et al., 2014), their detrimental role to set up suitable ecological niche of marine living resources including top predators like tuna. For example, our results show that low kinetic energy values (<0.1 m2s-2) or sluggish currents, seems to influence tuna catch (Figure 2b), and low effect in values > 0.1 m2 s-2. The flattened trend of tuna catch depicted, even at the strong eddy kinetic energy, could be related to the directions of the south-west surface currents (heading), which possible drove FADs and tuna associated species to aggregating tuna catch along the eddies periphery, mainly in the continental shelf of Madagascar coast (hotspots of tuna catch shown in Figure 1.2b bottom left). This finding is in contrast with dispersal effect of kinetic energy and current heading for marine organism (Peters and Marrase, 2000; Reigada et al., 2003), and corroborated with Dell et al. (2011) and Tew-Kai and Marsac (2010), whose found positive relationship between eddy kinetic energy and tuna catch. The west-southward currents significantly impacted tuna accumulation. Influenced by circulation in the Mozambique Channel, subjected to anti-cyclone and cyclone eddies with origin in the northern part of the channel, propagating west-southward (de Ruijter et al., 2002; Lutjeharms and Town, 2006; Swart et al., 2010), all contribute to the foraging behaviour of tuna through FAD driving or by accumulating and diffusing preys, and shaping the availability of food in the area (Chassot et al., 2019). Salinity, where tuna catch was associated around FADs, ranged from 31 g Kg-1 to 35 g Kg-1, in concordance with previous studies for tropical tuna species (Druon et al., 2017 Arrizabalaga et al., 2015). Tuna catches accumulated around FADs at low values of sea surface height, usually is related with low intensity of mesoscale eddies (Tew Kai and Marsac, 2009; José et al., 2014), which is known to effect attracting top predatory like tuna to the eddy periphery (Fonteneau et al., 2008; Tew Kai and Marsac, 2010).

The utility of GAM using environmental and spatio-temporal variables to predict the seasonality of tuna catch hotspots in this study was also demonstrated for FSC sets. Tuna showed preference for waters changing their temperature by ±1.5ºCover a week period, although FSC seems to prefer waters of 27ºC to 31ºC, being relatively close to productivity areas, where they can feed (Fiedler and Bernard, 1987; Mugo et al., 2014; Duffy et al., 2017).These results are consistent with previous studies, which have demonstrated that tropical tuna prefer moderately warm waters; (Zagaglia et al., 2004; Lee et al., 2005; Lan et al., 2011; Rajapaksha et al., 2013; Mugo et al., 2014; Arrizabalaga et al., 2015). Primary production, as reflected in chlorophyll concentration shows that in FSC, tuna catch aggregation was negatively related with production. This is because top predators like tunas do not directly consume primary production but feed on micronekton aggregations sustained by them (Potier et al., 2004; Potier et al., 2007). Productivity of this water can be influenced through sea surface height generated from eddy circulations, which the positive effects have been recognized in previous studies (Fonteneau et al., 2008; Fraile et al., 2010; Tew-Kai and Marsac, 2010; Brodie et al., 2015), by attracting tuna to eddy periphery or fronts (Fonteneau et al., 2008; Tew-Kai and Marsac, 2010), which in our results were between 0.3m to 0.8m. The tuna species targeted by FSC, aggregated catch in water with salinity between 33 and 35 g Kg-1, these salinity values are in concordance with previous studies for tropical tuna species (Druon et al., 2017; Arrizabalaga et al., 2015).

In contrast to the FADs sets, where the hotspots of tuna catch are located in west coast of Madagascar, for FSC sets, GAM detected the hotspots of tuna catch in northern tip of the MZC below 12º S. Difference between FADs and FSC fishing mode revealed partial overlapped of tuna catch, which could be attributed to oceanographic features such as surface currents (kinetic, velocity, heading), and eddy circulation due their effect on driving and aggregating plankton and prey. Also, it should be noted that purse seiners operate opportunistically on FADs or FSC mode irrespective the location.

Previous studies (Tew-Kai and Marsac, 2009) found that the seasonal productivity was more evident in north of 16ºS and south of 24ºS parts of the MZC, whereas the central area was less related to seasonal cycles, due to mesoscale dynamics. African river run-off, mesoscale cyclone and anti-cyclone eddies circulation also control the chlorophyll concentration and productivity dynamics in the MZC (Tew-Kai and Marsac, 2009; Omta et al., 2009; José et al., 2014), by injecting nutrients in the marine surface from continental coast or deep-sea regions. Chlorophyll enrichment increases energy flows in marine ecosystem through trophic pathways, and significantly influences distribution of marine species of any trophic level (Lali and Parsons, 2006; Tew-Kai and Marsac, 2009; Omta et al., 2009). Because of that, CHL concentration has been considered as a good proxy for prey availability in an area. Patches where the dynamics of phytoplankton bloom occur have been detected through remote sensing and documented in the literature as good areas for large pelagic fish abundance (Tew-Kai and Marsac, 2010; Chassot et al., 2011; Abdellaoui et al., 2017). This information has been exploited by fishermen who use remote sensing data to identify potential hotspots or fishing grounds (Fonteneau et al., 2008), mainly for FSC sets attracted through trophic level. The role of oceanic currents on the redistribution of plankton, micronekton, heat, oxygen and nutrients fluxes has been widely recognized (Fu, 1986; DiMarco et al., 2002; Bryden and Beal, 2001; Anilkumar et al., 2006; José et al., 2014). Dell et al. (2011) and Tew-Kai and Marsac (2010) with a positive relationship between eddy kinetic energy and tuna catch. However, it seems that the west-southward currents impacted the bulk of tuna catch observed in west side of Madagascar for FADs sets. Probably, the circulation in the Mozambique Channel, subjected to anti-cyclone and cyclone eddies with origin in the northern part of the channel, propagating west-southward (de

Ruijter et al., 2002; Lutjeharms and Town, 2006; Swart et al., 2010), was the driving force for the hotspots of tuna catch detected by GAM around FADs.

GAM was able to predict with reasonable accuracy patches where tuna catch was accumulated in the Mozambique Channel for FADs and FSC set types, threw non-linear relationship with environmental variables. Because of that, GAM is known as powerful tools to predict fish distribution and catch aggregations in marine habitats (e.g.: Maury et al., 2001; Murase et al., 2009). However, improvement of GAM to include additional environmental variables, such as oxygen concentration due to it collinearity with others important variables (Zuur et al., 2010; Dormann et al., 2013), and inclusion of other parameters like depth, front indices, zooplankton and micronekton indices would likely improve current models and provide complementary information. Availability of oxygen and zooplankton has been considered as key parameters for large pelagic species, including tuna (Stramma et al., 2011; Huggett, 2014; Potier et al., 2014). Dissolved oxygen depletion and vertical expansion of the oxygen minimum zone has been identified as one of the most important factors necessary to maintain current species distributions as it may restrict foraging habitat for tuna as well as the usable habitat (Stramma et al., 2011). Thus, future studies should consider specific analysis on this issue to better understand the implications of dissolved oxygen in the area and its relationship with tuna.

The results obtained in this study can be used as a first step to better understand the relationship between tuna and environmental parameters in the very dynamic MCZ area. Characterization of hotspots of FADs and FSC fishing regions could contribute to development of better conservation and management measures of the exploited species by purse seine fleets in the area to assure short, medium and long-term sustainability of the species and the fishery. Differences obtained between

FADs and FSC modes in environmental models reinforce the necessity to incorporate oceanographic information in the assessment and management processes for tropical tuna fisheries. Species have been traditionally managed using static non-adaptive measures. However, models identifying fishable hotspots where catch accumulates, like the one presented in this document, can be used to develop more adaptive and dynamic management approaches. Some examples of that can already be seen in large pelagic fisheries of Australia (Hobday et al., 2011) and the California Current (Hazen et al., 2018). Further research should consider detailed analysis on the use of similar approaches for the tropical tuna fisheries worldwide, and particularly, in the WIO region.

1.6. Conclusion

This study used medium-term time series (eleven years) logbook catch data, to show that the dynamic effect of the environmental oceanographic variables on tropical tuna catch accumulation along the Mozambique Channel varies according to the fishing mode. The models predicted suitable habitats for FAD associated fish between 10ºS to 18ºS, with the core, in general, in the north-western coast of Madagascar. Predictions for FSC suitable habitat shows that the core is principally found in the northern part of the Mozambique Channel, and also close to Mozambique coast between 10ºS to 16ºS. In this research, sea surface temperature and its variability, productivity, sea surface height, and the interactions of spatial and temporal variables were significant for both fishing types. However, geostrophic currents, showed significant effect for FAD catch accumulation only. The results obtained in this investigation highlight a connection between the biophysical state of the oceans and purse seine tuna fisheries in the MZC. This may contribute to the knowledge base required for the appropriate conservation of the exploited resources in the area, and support science-based decision making and management in a constantly changing oceanic ecosystem like the Mozambique Channel.

Acknowledgments

Authors would like to thankful the IEO Madrid, for data providing and technical support. This is extending to AZTI-Tecnalia for additional support in modelling and providing environmental data. This research was conducted at University of Alicante as part of the PhD study of Anildo Nataniel, at the Department of Marine Science and Applied Biology. The acknowledgement is extending to Dr Jack Littlepage, Emeritus Professor from University of Victoria (Victoria Canada) for Technical English Language review provide to this article.

Chapter 2 - Modelling the impacts of climate change on skipjack tuna (Katsuwonus pelamis) in the Mozambique

2.1. Abstract

Skipjack tuna play a significant role in global marine fisheries and are of particular interest for socio-economy in the tropical waters of the Mozambique Channel. However, human-induced climate change has been leading to a reduction and reallocation of catches, along with other ecological changes, thereby creating a feedback loop with negative socioeconomic consequences for fisheries-reliant coastal communities. The objective of this study was to predict the potential skipjack tuna fishing grounds by 2050 and 2100. To that end, skipjack tuna catch data were collected from Spanish purse seine fleets and subsequently Generalized Additive Models were used to model these data against a combination of environmental variables and future pathway projections from BIO-ORACLE models under optimistic (RCP2.6) and pessimistic (RCP8.5) scenarios. Both optimistic and pessimistic scenarios by 2050 predicted that the potential fishing grounds will relocate southward from tropical to more temperate waters, with moderate shifts in the potential fishing grounds of purse seines to the latitude >16ºS. Whereas the pessimistic scenario predicted higher displacement catches of purse seines in the southernmost part (>24ºS) and moderate to high catches in northern (>20ºS) of the Mozambique Channel by the end of the century Despite the degree of uncertainty surrounding the climate change impacts on skipjack tuna we argue that fisheries stakeholders, administrators and regional tuna fisheries management organizations should work toward building resilience and ensuring sustainability while reducing or mitigating vulnerability and climate change impacts on local and regional communities and their livelihoods.

Keywords: Climate change impacts, Mozambique Channel, purse seine fisheries, skipjack tuna, predicted skipjack catch, GAM

2.2. Introduction

Climate change, including increased global warming, ocean acidification, and ocean deoxygenation (Gruber, 2011; Ramírez et al., 2017), is a growing global concern and can lead to changes in the marine physicochemical and biological environments (Ramírez et al., 2017) and thereby modify net primary production, ocean circulation and fish abundance and distribution (Lehodey et al., 2010; Dueri et al., 2014).

In the marine ecosystem of the Western Indian Ocean (WIO), which includes the Mozambique Channel (MZC) climate change is expected to lead to increased temperatures, a slowdown of ocean circulation and a decrease in primary production (Mcclanahan et al., 2011; Popova et al., 2016). Moreover, this increased warming is expected to occur at a faster rate than in other tropical ocean regions (Roxy et al., 2014). With respect to the global distribution of marine species, tuna strictly depend on optimal temperatures, along with other oceanographic and environmental variables (Lopez et al., 2017; Orúe et al., 2020). Thus, considering the predicted changes induced by a warmer climate, it is expected that tuna will migrate from their original habitats to regions of higher latitude, upwellings, deeper waters and near eddies and fronts (Dueri et al., 2014; Marsac, 2017; Lecomte et al., 2017; Marsac, 2017; Monllor-Hurtado et al., 2017). Consequently, ecosystem responses to these climate impacts may lead to changes in catch volumes and, subsequently impact the national economies and livelihoods of WIO coastal states (Sumaila et al., 2011).

Among tropical tuna species the skipjack tuna (*Katsuwonus pelamis*) is the most caught tuna by industrial and small-scale fisheries in the FAO area 51 (POSEIDON et al., 2014; Mukesh et al., 2019). Between 1989 and 2019, the total skipjack catch from FAO 51 fishing grounds was about 9,000,000 tonnes, about 56% were fished by industrial purse seines, 11% by semi-industrial fisheries, and 33% from small-scale fisheries respectively (IOTC, 2020 Database). Over the last decade, skipjack have accounted for about 60% of all tropical tuna catches in the MZC high seas

(Chassot, et al., 2019). In the coastal waters around MZC, small-scale skipjack fisheries catches were reported to be ~43 thousand tonnes for the entire period between 2014 and 2019 inclusive (IOTC, 2020 Database). However, this number is thought to be much higher given that statistics from small-scale fisheries were under reported to the regional fisheries management organization: the Indian Ocean Tuna Commission (IOTC) (Chassot et al. 2019). Thus, it is evident that skipjack tuna from industrial, semi-industrial fleets and small-scale fisheries significantly contribute to the economy and livelihoods of WIO states by regularly supplying canneries and supporting local and regional food security (POSEIDON et al., 2014; Lecomte et al., 2017).

Skipjack tuna movement between marine economic exclusive zones within the MZC determines the interests and relationships among countries and industrial and small-scale fisheries. Previous studies carried out by Fonteneau and Hallier (2015), and Chassot et al. (2019) have demonstrated the complex movements of skipjack tuna between the northern MZC toward the south and northernmost areas out of the channel. This migratory behaviour is related to seasonal variations (Campling, 2012; Kaplan et al., 2014) and linked to an environmental habitat suitability dependent on water temperature, feeding forage and oxygen concentration (Lehodey et al., 2013; Dueri et al., 2014). Variables, such as sea surface height, currents (speed, kinetic energy, and direction) and mixed layer depth have also been considered to investigate tuna distribution and habitat preferences (e.g., Mugo et al., 2010; Yen et al., 2016; Lopez et al., 2017; Orúe et al., 2020; Orúe et al., 2020a). However, studies analysing climate change impacts on the area are either scarce or non-existent.

Although the exploitation of skipjack tuna stocks in the Indian Ocean is currently considered to be sustainable (IOTC, Database) skipjack tuna are highly sensitive to environmental conditions and changes (Loukos et al., 2003;Yen et al., 2016; Orúe et al., 2020). Given that climate change impacts will be particularly significant in marine ecosystems any variation in environmental factors may lead to changes in fish distribution and catchability (Dueri et al., 2014). Earlier studies have attempted to project the distribution and abundance of skipjack tuna elsewhere under climate change scenarios using APECOSM-E (Apex-Predator-Ecosystem-Model – Estimation) (Dueri et al., 2014), and catch aggregation, using SEAPODYM (Spatial Ecosystem and Population Dynamics Model) (Lehodey et al., 2013) and Generalized Additive Models (GAMs; Yen et al., 2016) and their findings suggested that climate change scenarios could lead to significant large scale changes to the distribution and habitats of skipjack tuna.

In this study we attempt to predict the effects of climate change on the distribution of skipjack tuna using GAMs, by analysing Spanish purse seine fisheries in the MZC. Specifically, we intend to (i) identify which biotic or abiotic characteristics most affect skipjack tuna catch distribution; (ii) predict the distributional shifts of skipjack tuna by the years 2050 and 2100 under optimistic and pessimistic climate change scenarios; and (iii) discuss the consequences of changes to species distributions and catch rates.

2.3. Methodology

2.3.1. Study area

The MZC is located in the southwestern Indian Ocean, with Mozambique to the west, Madagascar to the east and the Comoros archipelago to the north (Figure 2.1). The MZC is a particularly good place to investigate the relationship of a species with the environment as the current flows in the north of the channel are fed by warm South Equatorial Currents (SEC), which generate large eddies around the Comorian basin (Lutjeharms and Town, 2006; Ternon et al., 2014). From the narrows area of the channel (~16ºS) mesoscale eddies are formed, and progress from here southward, merging with those eddies generated in south-eastern Madagascar and move westward, where they become trapped by the Agulhas Current ~27ºS, moving southward (de Ruijter et al., 2006; Lutjeharms and Town, 2006; Ternon et al., 2014) (Figure S2, Spp. A). The effects of physical and biological oceanographic variables on the distribution of tuna schools appear to be seasonal in the MZC. For example, at the onset of the austral winter months (March-May) environmental conditions seem to be more suitable for tuna schools in the MZC (Kaplan et al., 2014; Obura et al., 2018) and attract purse seiners to fish in the northern part of the channel (Davies et al., 2014). Skipjack catches by industrial purse seines in the MZC are rare throughout the rest of the year (Campling, 2012; Kaplan et al., 2014; Chassot et al., 2019).

.

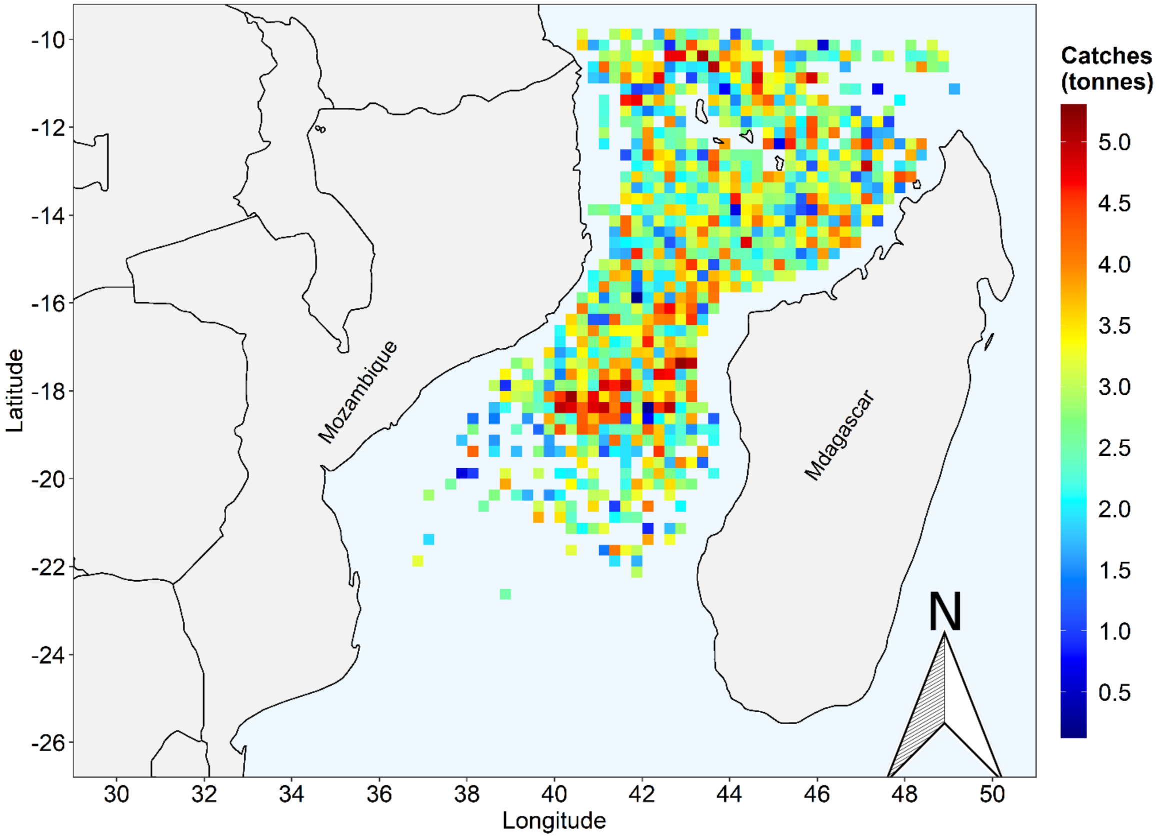


Figure 2.1 - Skipjack tuna catches (tonnes) distribution in the Mozambique Channel targeted by Spanish purse seine fleets for the period 2003 - 2013 (RPS). Catches aggregated were monthly by 0.25° x 0.25° resolution and displayed in the map at the logarithmic scale.

2.3.2.Fisheries Data

Fishing logbooks from Spanish tropical tuna purse seine fisheries were collected by the Spanish Oceanographic Institute for the period February 2003 - June 2013 (hereafter: RPS - Reference Period of the Study). The data were spatially restricted to the MZC, within the latitudes 8ºS to 30ºS and longitudes 30ºE to 50ºE (Figure 2.1). These data consist of 13,630 fishing set observations (49% in FSC - Free-Swimming Schools and 51% in FAD - Fish Aggregating Devices), with information on catch compositions, fishing hours, date (year, month, and day of the fishing operation), and location (i.e., longitude and latitude). Data were restricted to the months between March and May, which represent the fishing season for industrial purse seiners in the MZC. The distribution of skipjack catches data, shows that both purse seine set types (FAD and FSC) share the fishing grounds over the area (Figure S7, Supp. A), with high catches records in western side of Madagascar Island and northern of Comoros Islands (Figure 2.1). Because of the shared fishing grounds and the uncertainty to discriminate between free and associated schools of skipjack (Moreno et al., (2016)), all fisheries data were combined in this study.

2.3.3. Environmental Data

Environmental data for the MZC for the period 2003-2013 (RPS) was downloaded from the MyOcean-Copernicus EU consortium (CMEMS; marine.copernicus.eu) in netCDF format and extracted for each fishing set location and date through specific codes and routines using functions from the packages netCDF4 (Pierce, 2017), chron (Jame and Hornik, 2013), and lubridate (Grolemund and Wickham, 2011), and other basic functions in version 3.6.0 of R software (R Core Team, 2018). The environmental factors included were: sea surface temperature (SST, ºC); sea surface temperature gradient (SSTGD, ºC), which was derived from the decrease or increase in temperature for each pixel over a 7-day period; sea surface height (SSH, m); eddy kinetic energy

(KE, derived from altimetry, m^2 s^{-1}); current sea surface heading (HDG, degrees); current sea surface velocity (SSC, m s^{-1}): chlorophyll-a concentration (CHL, mg m^{-3}); chlorophyll-a concentration gradient (CHLGD, mg m^{-3}, derived from the decrease or increase in CHL concentration for each pixel over a 7-day period); sea surface salinity (g Kg^{-1}), and Oxygen concentration (O_2, mg l^{-1}). The spatial and temporal resolutions were 1/4° and daily, respectively (Table S1, Supp. B). All the variables were extracted from the CMEMS product GLOBAL_REANALYSIS_PHY_001_031, except chlorophyll-a and oxygen concentrations which were downloaded from the product GLOBAL_REANALYSIS_BIO_001_029. These variables were assumed to be potentially related to skipjack tuna as several studies already explored or evidenced the importance of these relationships (e.g., Loukos et al., 2003; Lehodey et al., 2013; Mugo et al., 2010; Dueri et al., 2014; Yen et al., 2016). Spatial-temporal variables, such as longitude, latitude, year, month, and natural day, (i.e., from 1 to 365 days) were also incorporated into the models because they can help with spatial-autocorrelation and may explain part of the variability on catches not explained by other environmental variables and spatially structured processes (e.g., other abiotic and biotic factors and processes) not included in this study (Cortés-Avizanda et al., 2011). The oceanographic and spatio-temporal variables considered here have been used by other studies to model tuna and other large marine predators, habitats, environmental preferences or fishing hotspots (Table 1.1).

Intergovernmental Panel on Climate Change (IPCC) surface temperature projections were used to model future scenarios (IPCC, 2014). Specifically, we accessed the Representative Concentration Pathways (RCP) 2.6 and 8.5 for the years 2050 and 2100 (radiative forcing levels of approximately 2.6 and 8.5 Wm^{-2} by the end of 2100, respectively) for monthly mean sea surface temperature with a spatial resolution of 0.083º x 0.083º grid cells from Bio-ORACLE (http://www.bio-oracle.org). The RCP2.6 (optimistic) emission scenario assumes the least change, with a temperature increase of

1ºC by 2050 and 2º C by 2100 and a salinity increase of 0.5 PSU and 1 PSU units for these same years, respectively. The RCP8.5 (most pessimistic) scenario, by contrast, presumes more severe changes, with a temperature increase of 1.5º C by 2050 and almost 3º C by 2100, and a salinity increase of 1 PSU and 1.5 PSU units for these same years, respectively (Meinshausen et al., 2011; IPCC, 2014).

2.3.4. Model construction and projection

In an exploratory phase, the relative importance of covariates on skipjack tuna catch was assessed using the randomForest package (Liaw and Matthew, 2002), and the most important covariates were selected to reduce model complexity and redundancy in later fitting stages (Dell et al., 2011). Additionally and following Zuur et al. (2010) correlation among variables was tested using the Pearson correlation rank (rho), and only variables with a *rho* absolute value lower than 0.70 were included simultaneously in the GAMs (Dormann et al., 2013). Finally, a variance inflation factor analysis was also conducted using a threshold value of 3 as a supplementary measure to test collinearity among explicative variables (Zuur et al., 2009). The covariates natural day, current velocity and dissolved oxygen were dropped for further modelling due to collinearity and correlation with ecologically more important environmental variables.

In the first steps of model construction, the daily set by set data were used as response variables. However, the model underperformed and failed to detect the changes in variance at this scale, therefore, data were aggregated by month to a 1/4º grid cell (i.e., the sum of the catches and the mean of the environmental variables). Details to create different scale grids and raster layers through the raster package can be found in Bivand et al. (2015). GAMs (Wood, 2006) were established by using the new positive gridded data to examine the effects of environmental variables on the spatio-temporal skipjack distributions. The logarithmic transformation of skipjack tuna catches (i.e., log (Catch+1)) was used as the dependent variable to reduce skewness and improve model performance (Zuur et al., 2010). The logarithmic transformation was applied also to the covariates CHL and KE to improve contrast and model fitting. GAMs were fitted with a Gaussian family by using the identity link function and applying the *mgcv* package (Wood, 2006), and followed the procedures to model continuous data (Wood, 2006; Zuur et al., 2009) and distribution data tests (Delignette-Muller and Dutang, 2015).

GAMs are semi-parametric extension of Generalized Linear Models (GLMs) (Guisan et al., 2002b) for which the strictly linear predictor:

$$g(\mu(\mathbf{X})) = \beta_0 + \beta_1 X_1 + \cdots + \beta_p X_p,$$

where $\mathbf{X} = (X_1, \ldots, X_p)$ are covariables, $\mu(X) = E\ (Y\ |X)$ is the conditional exception of the response variable Y, g is the link function (explained below) and β_0, $\beta_1, \ldots, \beta_p$ are the unknown parameters, is replaced by

$$g(\mu(\mathbf{X})) = \beta_0 + f_1(X_1) + \cdots + f_p(X_p),$$

where $f_j(X_j)$ is the unknown smooth partial effect of X_j on the predictor. Hence GAMs avoid the assumption of linear relation between the response variable and the covariables providing a more flexible model. Note that GLMs are an extension of Linear Models for which the distribution of the response variable can be other than gaussian. For this reason, in the previous models a link function g is applied to $\mu(X)$. Using the syntax of the *mgcv* R package, the GAM was fitted as:

$$\begin{aligned} \ln(\text{Catch}+1) \sim\ & te(\text{space-time}, k=(50,6), d=c(2,1) + \\ & s(C_a, C_b, k=20) + s(C_c, k=6) + s(C_d, k=6) + \ldots + \\ & s(C_z, k=6) + c(C, k=6) + \mathit{random} \end{aligned}$$

where *te* function forms the product from the marginal terms of the space-time triple interactions; *d* is the dimension of each spline in the triple interaction (which in this case is two for spatial components and one for temporal terms); and *s* is the penalized spline smooth function for single interactions and environmental covariates (C). All interactions were fitted by the tensor smooth (ts) product whereas the single covariates were fitted with cubic spline regressions (*cs*) to model nonlinear relationships. Cubic spline regressions ensure that: a regression spline with shrinkage is applied, that a smoother can have zero degrees of freedom, and that all smoothers with zero degrees of freedom can be simultaneously dropped from the model (Zuur et al., 2009). A cyclic cubic regression spline, *c*, was used to illustrate the cyclical behaviour of the terms (e.g., Heading) (Wood, 2006). Finally, a random effect was included (i.e., year) to account for inter-annual variability in fishing effort and fleet behaviour (Brodie et al., 2015; Lopez et al., 2020). Dimension, denoted by *k*, was used to represents the maximum degrees of freedom allowed for each smooth term and was set to k = 6 for the main effect, k=20 for the first order interaction (Cardinale et al., 2009; Giannoulaki et al., 2013; Jones et al., 2014), and k=50 for spatial components in the space-time triple interaction after trial error (Wikle et al., 2019) to avoid model overfitting and to simplify the interpretation of results. After the first model simulations, 5% of residual data noise was excluded, i.e., 95% of data were absorbed into the model either without or with less outliers (Zuur et al., 2010) to improve model robustness.

The backward selection method with a residual deviance score, a Generalized Cross Validation (GCV) score, an Akaike information criterion (AIC), a residual check (Wood, 2006; Zuur et al., 2009) and a residuals spatial autocorrelation test (Bjørnstad et al., 2001), were the criteria considered to determine the best model .

A k-fold cross-validation was applied (James et al., 2014), which consists of randomly splitting observations into k groups, (in this study k was set to 10 folds) to validate and assess model performance. The first fold was treated as a test dataset to validate the prediction of schools aggregation in fishing grounds and the model was fitted to the remaining $k - 1$ folds, which was treated as a training dataset (James et al., 2014). Next, the root mean square error rate (RMSE), Pearson correlation score (rho) and Schoener similarity index D (Zhang, 2016) between predicted and observed values, were computed to measure the accuracy and predictive performance of the model on the held-out fold validation data.

Finally, the model was built with environmental data and used to project skipjack tuna catch distribution into the future (2050 and 2100) according to the RCP2.6 and RCP8.5 climate change scenarios (Assis et al., 2017). The RCP2.6 and RCP8.5 climate change scenarios predict the lowest and highest rises in global temperatures from greenhouse gas concentrations respectively (Moss et al., 2010; Meinshausen et al., 2011). The climate variables available in BiO-ORACLE were used to predict future scenarios (i. e. sea surface temperature-SST) whereas the remaining variables used to construct the model were set to zero given that the goal was to predict based on SST changes - the main proxy for climate change intensity scenarios. SST has been considered one of the best factors to predict the ecological niche of skipjack tuna (e.g.: Mugo et al., 2010; Dueri et al., 2014), as it influences skipjack physiological abilities and migratory behaviour (Graham and Dickson, 2004), affects optimal feeding forage and growth rates (Barkley et al., 1978) and limits spawning aggregation among schools in both northern and southern latitudinal waters where temperatures average >24ºC isotherms (Matsumoto et al., 1984; Schaefer, 2001). Besides, SST is a good proxy for, or is connected to, other environmental variables and processes (e.g.: Lali and Parsons, 2006; Mann and Lazier, 2006; Miller and Wheeler, 2012; Gruber, 2011; Popova et al., 2016; Rahmstorf, 2007; Aral et al., 2012; Aral and Guan, 2016). Furthermore, SST data from Bio-ORACLE have been widely used to predict the potential distribution of marine species under different climate change scenarios (e.g., Tyberghein et al., 2012; Duffy et al., 2016). Changes to skipjack distribution was assessed by estimating the differences in spatial predictions of each ¼º square cell between projected future and reference period scenarios (e.g., Dueri et al., 2014; Yen et al., 2016). All analyses were conducted using R version 3.6 (R Core Team, 2018).

2.4. Results

2.4.1. Model performance

The relationships between skipjack tuna catches and the environmental parameters examined in this study are summarized in Table 2.1, along with model parameters (estimated degrees of freedom -EDF, explained deviance, AIC and GVC scores), the proportion explained by model terms and the statistical significance of covariates. All variables selected in the model where highly significant (p-values < 0.01). The k-fold cross validation statistics, i.e., accuracy metric measure (RMSE), Pearson correlation (rho) and similarity index (D) between predicted and observed values, were reasonably good (RMSE ~ 0.08, rho ~ 0.37, D=0.88), which suggests good model performance. Furthermore, the goodness-of-fit for model met the basic criteria as confirmed by residual checking, i.e., residual graphic inspections using spline correlograms did not display spatial autocorrelation. Also, residual of histogram normal distribution, homogeneity of variance, and the straight linearity between fitted values and response criterions were met (Figure S6, Supp. A).

Table 2.1 - Selected GAM model of skipjack tuna distribution in the Mozambique Channel. Models were fitted with Gaussian distributions with identity links. EDF: effective degrees of freedom, SSH: sea surface height, CHL: chlorophyll-a, SST: sea surface temperature, SSTGD: sea surface temperature gradient, HDG: heading (sea surface currents direction), KE: kinetic energy. Long: Longitude in degrees. Lat: Latitude in degrees. Dev. Covariate: is deviance explained by each covariate term in the model. Dev. Explained is the deviance explained by all covariates in the model, AIC Akaike Information Criterion. F-Statistic: give the ratio between deviance explained and not explained by covariate.

Parameters	**Mode output fitted by Gaussian family identity link function**			
Adjusted R^2	0.13			
Dev. Explained. (%)	15.60			
AIC score	8188.00			
GCV score	0.69			
n	3328			
EDF	88.88			
Residual df.	3239.12			
Covariates	***EDF***	***p-value***	**Dev. Covariate**	**F-Statistic**
CHL	2.70	<0.01	0.37	2.41
HDG	3.61	<0.001	1.22	8.52
SSH	3.17	<0.001	0.69	4.25
KE	2.64	<0.001	0.73	4.90
Year	0.02	<0.001	0.13	0.69
SST x SSTGD	11.70	<0.001	2.39	4.13
Long x Lat x Month	64.03	<0.001	10.44	1.70

2.4.2. Environmental effects

The effects of all environmental factors on skipjack tuna catches are shown in Figure 2.2. The spatial-temporal interactions (Longitude x Latitude x Month), shows that skipjack tuna aggregated more in west coast of Madagascar at the latitude <18ºS whereas in the Mozambique coast the effects of the spatio-temporal interactions depicted negative catches at the areas <40.5E/16ºS between March-April and at the longitudes <39ºE in May (Figure 2). The fishing cores were predicted at the section >42ºE and <17ºS, mostly in the west tip of Madagascar. This was the most important term in the model, contributing to about 10% out of ~16% of the total model deviance (65% of the total). The interaction SST x SSTGD was the second most important term (contributed to ~2.40% in model deviance, 15% of the total). Skipjack tuna tends to aggregate more in warm waters (SST >27ºC) particularly where temperatures changed by ±1ºC over a week period. Sea surface current direction (HDG) with ~1.20% of contribution in model deviance (8% of the total), is the third most important ecological variable. The shape of functional forms for HDG revealed that skipjack tuna was most caught when the currents were moving in southward and northwest directions (Figure 2.2) which could be related to the anti-cyclone gyres generated around Comoro Islands. Skipjack catches shown high variance at the lowest and highest chlorophyll concentration values and an optimum range at medium levels (Figure 2.2). The shape of functional forms indicated an increase in skipjack tuna at sea surface height values between 0.5-0.6 m. Skipjack tuna catches were positively correlated with KE especially at medium levels (Figure 2.2). Together, CHL, SSH, and KE account with ~1.8% in the model deviance (11% of the total) (i.e,. each covariate contributes with less than 1%).

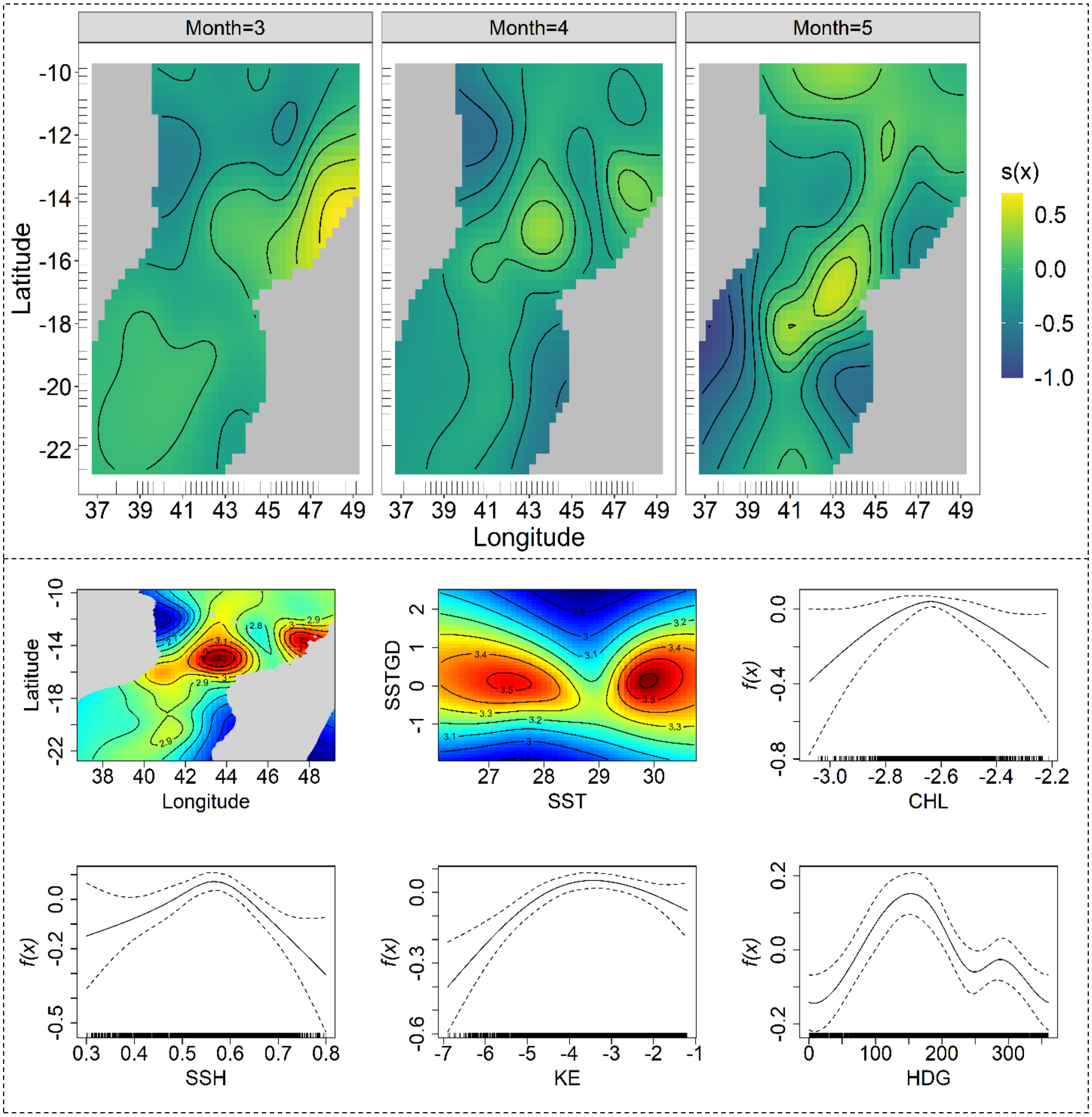


Figure 2.2 - Partial effects of environmental factors on the skipjack tuna catches of the Spanish purse seine fleets in the Mozambique Channel. The top panel displays the space-time effects, and the bottom panel displays the oceanography variable effects. Tick marks on the x-axis represent the observed data. The y-axes, denoted as f(x), represent the relative importance of the model's predictor variables. Dashed lines indicate the lower and upper 95% confidence intervals of the smooth plot.

2.4.3. Projected skipjack tuna distribution in future scenarios

Table 2.2 summarizes the percentage of changes to the areas where skipjack tuna distribution is projected under the future climate change scenarios. Current skipjack fishing observed areas covered ~25% of the Mozambique Channel, whereas the overall projected area changes for skipjack tuna aggregation is ~84%. Model results for the RCP2.6 scenario (Table 2.2) predicted major changes in size of SKJ habitat from the RPS to 2050, i.e., the fishing areas would change (sum of loss and gain) by about ~93% in the MZC (+1.5% of absolute gain). Between the RPS and 2100, the models also revealed major area changes, by ~90% (+4.3 of absolute gain). However, for the period 2050-2100 the models projected that the fishing areas for skipjack tuna would minor to 10% (-9.3 of absolute gain). The area changes to skipjack tuna schools predicted by the RCP8.5 scenario (Table 2.2) between the RPS and 2050 were about 90% (+3.7 of absolute gain) whereas from the RPS to 2100 changes were projected to ~88% (+79.7 of absolute gain). However, between 2050 - 2100 continuous change was predicted, i.e., >92% of all areas (+60.1 of absolute gain) were projected to see a shift in skipjack schools' distribution or displacement over the area of the Mozambique Channel.

Table 2.2 - Percentage of projected area changes for skipjack tuna catches accumulation under future climate change scenarios, by fishing mode. Unchanged areas (%) indicated by values around zero (0) anomalies; lost areas indicated by negative anomalies, and gained areas indicated by positive anomalies and correspond to the locations with skipjack catches aggregation. RPS - reference period of the study corresponding to 2003 - 2013.

RCP	**Year**	**Projection (%)**				
		Unchanged	**Loss**	**Gain**	**Gain + Loss**	**Gain - Loss**
RCP2.6	2050 - RPS	6.71	45.87	47.41	93.28	+1.5
	2100 - RPS	9.99	42.86	47.15	90.01	+4.3
	2100 - 2050	90.66	9.34	0	9.34	-9.3
RCP8.5	2050 - RPS	9.96	43.17	46.87	90.04	+3.7
	2100 - RPS	11.65	4.35	84.01	88.36	+79.7
	2100 - 2050	7.51	16.21	76.28	92.49	+60.1

When projected using skipjack catch model the differences between future and current scenarios under the RCP2.6 and RCP8.5 climate change scenarios predicted catch losses (negative signs), no changes (zero values) and/or catches gains (positive signs) within the MZC (Figure 2.3). Specifically, RCP2.6 predicted skipjack catch losses of ~ 46% and ~43% in northern latitudes (< 20ºS) from the RPS to the ends of 2050 and 2100 respectively (Figure 2.3a-b). Positive expansion of ~ 47% toward southern latitudes (> 20ºS) was projected by the end of both 2050 and 2100 (Figure 2.3a-b). Whereas between 2050 and 2100 no changes to skipjack tuna catches were predicted in ~91% of fishing grounds (Figure 2.3c).

With respect to the RCP8.5 scenario, by 2050 catches losses (~ 43%) and positive spreading (47%) were projected in latitudes both below and above 20ºS (Figure 2.3d). By 2100, the model predicted positive displacement of positive anomalies (84%) recovery of tuna catches at the latitude <20ºS and these were projected to increase in the southern areas of the MZC, with particularly high aggregation of tuna schools above 24ºS (Figure 2.3e). A loss and unchanged on tuna catches were predicted at the narrow area between 20ºS and 24ºS covering an area of ~16%. A comparison between the 2050 and 2100 future projections (Figure 2.3f) reveals that skipjack catches would be lost or unchanged around 20ºS-25ºS (~24%). By contrast, in the areas <20ºS and >25ºS the positively catch anomalies (~76%) were projected, with most accumulated in the north part of the MZC. The projections show displacement characterized by catch recovering (<20ºS) and expansion above 25ºS.

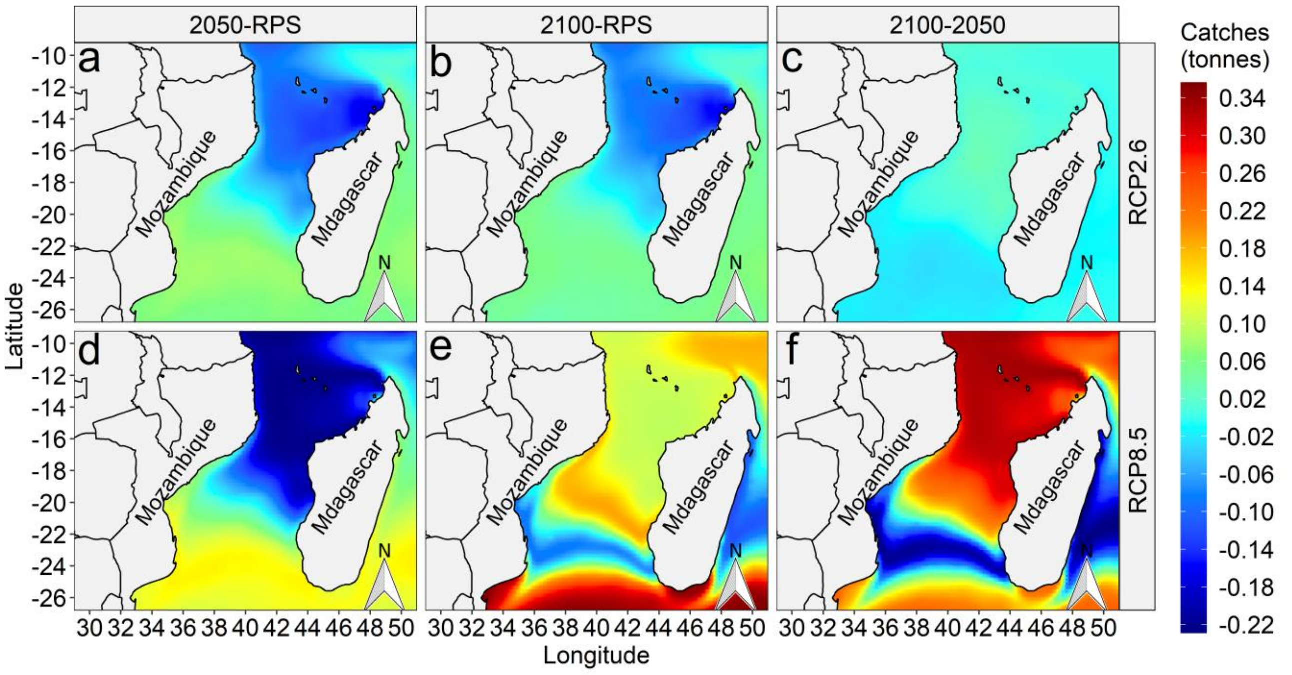


Figure 2.3 - Projected differences in skipjack tuna catches (tonnes) targeted by purse seine around free and associated schools between the RPS (2003-2013) and future (2050 and 2100) under the BIO-ORACLE RCP2.6 and RCP8.5 climate change scenarios. The first column (panel a and d) depicts the anomalies of predicted catches between layers 2050 and the RPS. The second column (panel b and e) show anomalies between layers 2100 and RPS, and the third column (panel b and e), display the anomalies between layers 2100 and 2050.

2.5. Discussion

The GAM used in this study to model skipjack catches performed well and had a reasonable level of predicting power (RMSE < 10%). As suggested in previous studies for selection of good predictive ecological models (e.g.: Fletcher & Fortin, 2018; Norberg et al., 2019; Wikle et al., 2019) we fit a small set of models showing complementary performance, and then apply a cross-validation procedure. The low deviance explained (~16%) could be related to the exclusion of other factors or processes in the model such as fine and large scale environmental processes, inherent biological and behavioural factors, processes related to the life-cycle of the species, as well as issues related with catchability and fishing operations (e.g.: Torres-Irineo et al., 2014; Lopez et al., 2014; Lopez & Scott, 2014; Moreno et al., 2016b). For example the complex bio-physical processes dominated by eddy circulation in the MZC (e.g.: Béhagle et al., 2014; Huggett, 2014), as well as details on the biology or the behaviour of the species (e.g. school fragmentation, density dependant behaviour) are hard to detect, quantify and integrate in traditional modelling exercises and could effect model performance. Further studies should explore the use of additional or complementary environmental and biological factors to investigate model performance, as well as descriptive and predictive power of models in relation to covariate selection. Similarly, periodic revisions of the current model, as well as the use of alternative projections for environmental data could help understand in the short-term the accuracy of the model and the sensitivity of using different data products by different climate-monitoring agencies.

The relationship between environmental variables and skipjack catches has previously been modelled using GAMs (e.g., Mugo et al., 2010; Yen et al., 2016), the SEAPODYM model (e.g., Loukos et al., 2003; Lehodey et al., 2013), and the APECOSM-E model (e.g., Dueri et al., 2012; Dueri et al., 2014). The relationship between environmental variables and other tropical tuna species have also previously been modelled (e.g., Arrizabalaga et al., 2015; Druon et al., 2017; Lopez et al., 2017; Monllor-Hurtado et al., 2017). However, previous studies have rarely modelled this relationship in the MZC. Among the oceanographic variables selected in the above cited studies, SST has been considered one of the best drivers to predict the ecological niche for many pelagic species (Hobday and Pecl, 2014) including skipjack tuna (Mugo et al., 2010; Dueri et al., 2014).

Changes to SST have been considered to influence skipjack physiological abilities and migratory behaviour (Graham and Dickson, 2004). Moreover, SST can affect optimal feeding forage and growth rates of the species below 15ºC and above 30ºC (Barkley et al., 1978) and limit spawning aggregation among schools in both northern and southern latitudinal waters where temperatures average >24ºC isotherms (Matsumoto et al., 1984; Schaefer, 2001). SST may also be a good proxy for other environmental processes as well. For instance, ocean warming could modify the circulation of currents by changing water density, decreasing primary production (low chlorophyl concentration) in the surface layer and displace essential nutrients in euphotic zones by stratifying water mass thereby affecting several trophic levels (Lali and Parsons, 2006; Mann and Lazier, 2006; Miller and Wheeler, 2012). Similarly, rising of SST could induce ocean deoxygenation (Gruber, 2011; Popova et al., 2016) along with continuous sea level rise (Rahmstorf, 2007; Aral et al., 2012; Aral and Guan, 2016). Alternately increasing warming could be positively correlated with motion intensification from cyclonic or anticyclonic eddies (Matyas, 2015) shifting the redistribution of trophic level and tuna species (Potier et al., 2014). The direction of surface currents (HDG-heading) may indicate where micronekton, zooplankton and other prey are driven by surface currents and concentrated in specific patches, potentially attracting tuna schools. Béhagle et al., (2014) found that the mesoscale features in the Mozambique Channel, either cyclonic and anticyclonic, exhibited greater micronekton density. Another study from Huggett (2014) suggest that mesoscale eddy and shelf interactions play a fundamental role in shaping the Mozambique Channel pelagic ecosystem through the concentration, enhanced growth and redistribution of zooplankton communities. The present study found significant relationship with several of the environmental variables mentioned above including SST and SST gradient, CHL, KE, SSH and direction of the currents. However, further ecological or habitat analysis are needed to better understand the effects of environmental variables on the species of interest including tuna and other important species to support economic and food security in the region.

The effects of climate change on marine ecosystems, particularly on tropical tuna species have become of general concern in recent years (Lehodey et al., 2013; Dueri et al., 2014; Monllor-Hurtado et al., 2017; Erauskin-Extramiana et al., 2019). In the MZC, skipjack tuna catches exhibited distribution trends that follow the general tendencies of climate change scenarios. More specifically, skipjack tuna under the RCP2.6 scenario are expected to move from the warm waters in the north injected by the SEC to the intermediate waters in the south fed by Agulhas Current (AC). Thus, following the trajectory circulation of cyclones and anti-cyclone eddies in the area (Figure S2, Supp. A). Similarly the RCP8.5 scenario indicated a potential southward displacement projection by 2050 in agreement with current and future potential eddy and water circulation (e.g.: Lutjeharms & Town, 2006; Swartet al., 2010; Ternon et al., 2014). In contrast comparisons between 2100 and RPS, and 2010-2050 projected recovering trends of skipjack catches in the area <20ºS, where warming is predicted to happen faster (Roxy et al., 2014). Perhaps, the complex mechanism of water mass circulation in the MZC such as the suggested possible dilution and mixing among the northward currents (e. g.: cold North Atlantic Deep Water – NADW and Antarctic Intermediate Water - AAIW), and southward currents (e.g.: Red Sea Water -RSW and North Indian Deep Water – NIDW) and South Equatorial Currents (SEC) within the Comorian basin (e.g.: Ullgrenet al., 2012; Collins et al., 2016; Charles et al., 2020). This coupled with the effects of cyclone and anti-cyclone eddies which exchange the water mass could probably explain the displacement with restoration trend in northern of MZC. Also, Warm water (SST ~28ºC - 30ºC) is also related to tropical cyclone formation and storm intensification (Suzuki et al., 2004; Matyas, 2015) promoting high evaporation and contributing to increase precipitation in the region which could act in favour of skipjack suitable habitat. Constant monitoring and investigation of the impacts of climate change in the oceanography of the area are necessary to better assess, understand and mitigate the potential environmental consequences in MZC waters and associated habitats for species of interest. Understanding the potential habitat distribution of a species like skipjack tuna could provide important information about future oceanic and coastal fishing grounds, and contribute to designing and implementing spatially-explicit management plans.

The Intergovernmental Panel on Climate Change (IPCC) has projected ocean warming in the top 100m at between 2ºC and 3ºC by the end of the twenty-first century depending on the severity of predictive scenarios (Collins et al., 2013). Pelagic species, such as skipjack tuna, may respond to climate change by shifting their geographical or bathymetric distribution and the intensity of school aggregations (e.g., Cheung et al., 2013; Barange et al., 2014; Monllor-Hurtado et al., 2017). The present study was conducted in the Mozambique Channel, which is considered to be one of the most important "warming hotspot" regions in the world (Hobday & Pecl., 2014; Popova et al., 2016). Model projections for both the optimistic and pessimistic climate scenarios suggest that climate change will redistribute skipjack tuna from the traditional areas in the north towards areas in the southern part of the Mozambique Channel by 2050 and 2100 (Figure 2.3). These results are aligned with findings from other regions of the Pacific Ocean, suggest potential catch may increase in waters that are currently cold (Dueri et al., 2014; Yen et al., 2016). Interestingly, the results showed by RCP8.5 scenarios for the period between 2100-RPS and 2100-2050 project catch restoration in areas predicted to warm significantly (Roxy et al., 2014; Popova et al., 2016). However previous studies have predicted that warm equatorial habitats will become less favourable for tuna (e.g., Loukos et al., 2003; Lehodey et al., 2013; Dueri et al., 2014; Lehodey et al., 2015; Monllor-Hurtado et al., 2017). Therefore, additional analyses are desirable in the future to test and investigate in detail potential differences and robustness of projections of skipjack tuna using different climate scenarios and data sources.

The results of our study show that under a low greenhouse gas emissions scenario (RCP 2.6) an increase in the potential distribution of skipjack catches will be favoured towards the southern waters of the MZC with relatively high favourable fishing grounds predicted to gain ~ +1.5% and ~4.3% by 2050 and 2100, and minor loss in total fishing grounds between 2100 - 2050 of about 9%. Similar patterns of catch anomalies at the start and the end of the century have been found in other regions of the Indian Ocean for skipjack as well (Dueri et al., 2014; Marsac, 2017). Whilst the change would be of limited impact and may not generate major stress for skipjack tuna under the optimistic scenario (Marsac, 2017) purse seine fleets may continue to fish skipjack across the predicted suitable habitats if the operations are economically viable. However, studies investigating the effects of climate change on fishing behaviour and the socio-economic implications on industrial and non-industrial fleets operating in the region should be promoted to guarantee that coastal and oceanic fisheries adaptation and resiliency plans are developed on time.

Changes to the distribution of tuna are expected to be more pronounced in the pessimistic climate scenario (RCP8.5) with an expansion of skipjack catches from the fastest warming northern area of the Mozambique Channel to the south (Roxy et al., 2014; Popova et al., 2016) by 2050 with gained habitat almost to +4% relative to lost area. The redistribution pattern of skipjack fishing grounds (Moss et al., 2010; Meinshausen et al., 2011; O'Neill et al., 2016) could be a major stress and may dramatically change skipjack fisheries and species' dynamics in the MZC. The fishing grounds where skipjack are expected to accumulate by the middle of the century have previously been predicted to be industrial tuna purse seine fishing grounds (Dueri et al., 2014; Marsac, 2017). However, by the end of the century positive anomalies of fishing ground displacement were predicted, with >60% relative to the lost, suggesting that fishing grounds will be located in northern of MZC (>20ºS). Under RCP8.5 (Figure 2.3d-f) model predictions locations may respond to the complex hydrographic water mass dilution and mixing around Comorian basin, and elsewhere in MZC (e.g.:Ullgren et al., 2012; Collins et al, 2016; Charles et al., 2020). These could include, cyclone formation, storm intensification, evaporation and heavy rainfall (Suzuki et al., 2004; Matyas, 2015), and can contribute to water mass mixing, nutrient recycling, heat flux exchange, and redistribution of dissolved oxygen These and other processes could make the northern of MZC a productive and favourable area for skipjac.

Climate change also interacts with other non-climate stressors such as overfishing, habitat disruption, illegal, unreported and unregulated fishing and marine pollution (Brander, 2008; Daw et al., 2009; Benkenstein, 2013).Thus it is one of the many stressors in marine socio-ecological systems impacting fisheries (Perry et al., 2010). Human and social systems could adapt to these unintended changes in several ways. For example by exploiting previously unfished resources, fishing in previously unfished locations or seasons (Brander, 2008), diversifying income sources, and/or developing policies and governing mechanisms to facilitate or promote resilience (e.g., Badjeck et al., 2010; Grafton, 2010; Kalikoski et al., 2010). Some communities in the northern area could be significantly impacted however communities in the central and southern areas of the Mozambique channel could benefit from the redistribution of skipjack resources. This disparity has previously been documented by Allison et al. (2009), who suggested that climate change could positively impact some communities in specific locations while harming others. Climate change is also expected to create socio-ecological uncertainties in coastal states (Badjeck et al., 2010; Grafton, 2010; Hanna, 2011). Besides the uncertainty surrounding the effects on bio-physical processes and how those effects flow through ecosystem services (Dulvy et al., 2011) and fish availability (Lehodey et al., 2011) climate effects may also change fish production costs associated with locating, harvesting, processing, storing and transporting catches (Hanna, 2011). The degree of uncertainty when it comes to the negative impacts of climate change on future distribution of tuna catches could potentially effect the economy and social well-being or livelihood of small-scale fisheries communities located in northern Mozambique Channel. On a regional scale the coastal states surrounding the MZC (e.g., the Comoros Islands, Madagascar, Mozambique, and Mayotte) could also suffer an impact on their economic revenues as a result of climate variability (Hanna, 2011; Dey et al., 2016), as industrial fleets with tuna access agreements reassess their fishing strategies and move toward the more temperate areas that are projected to have more favorable tuna fishing areas (Grafton, 2010; Perry et al., 2010; Hanna, 2011; Hobday and Pecl, 2014). Thus, long-term climate effects may impact existing fishing agreements between the Mozambique Channel coastal states and distant water fishing nations (Havice and Reed, 2012) with potential negative impact on socio-economic incomes for some African coastal states.

According to Allison et al.(2009) coastal nations along the MZC have a moderate to high dependence on fishing relative to their national economies, export revenues, and fish consumption. This and other investigatons found MZC coastal state nations vulnerability to climate impacts to be high and adaptive capacity to be low (Allison et al., 2009; Daw et al., 2009; Benkenstein, 2013). Therefore fishers, fisheries managers, and decision-makers around the Mozambique Channel are encouraged to take measures to make them more resilient and adapt to the socio-ecological and socio-economic uncertainty shift associated with climate change. Given that many small-scale fishers have been targeting tuna and tuna-like species in the northern part of the Mozambique Channel (Mutombene et al., 2017; Chassot et al., 2019) which is an area that is predicted to be significantly impacted by the year 2050 (e.g., Roxy et al., 2014; Popova et al., 2016),they will have to adapt to this new reality by targeting multiple species, shifting their fishing seasons or fishing sites and/or developing new fishing strategies (e.g., FAO, 2006; Benkenstein, 2013; Wanyonyi et al., 2016; Mutombene et al., 2017). For fishers with strong attachments to their communities, who are either unable or unwilling to move closer to these new fishing grounds may have to adopt more diversified and flexible livelihoods (Blythe, 2015; Lindegren and Brander, 2018). By contrast industrial fleets may respond to climate impacts by investing in advanced technical and innovative fishing technologies (Allison et al., 2009; Grafton, 2010; Perry et al., 2010; Hanna, 2011) in order to continue fishing the original target species.

The dilemma for fisheries stakeholders is when and how to adapt or be resilient when challenged with the uncertainties of marine resources and the effects of inevitable climate change. Thus, fisheries stakeholders operating in the Mozambique Channel should develop precautionary fisheries management plans to reduce the vulnerability of fishing communities even if these adaptation plans do not take effect for several years (Grafton, 2010). Climate change adaptation and mitigation strategies will vary according to the fishery as the degree of exposure, sensitivity, vulnerability and adaptative capacity differs according to marine ecological ecosystem, targeted species, operational characteristics of the fleet, and social groups (Daw et al., 2009; Grafton, 2010; Lindegren and Brander, 2018). Approaches to enhance the resilience of the fishing sectors, such as adaptative co-management or inclusive Marine Spatial Planning (MSP) (Pennino et al., 2021), which have been proposed to address uncertainty and harness the knowledge and commitment of fisheries resources at multiple scales, may be a good place to start. This study will contribute to increased awareness of the impacts of climate change on high ecological and socio-economic value fisheries, such as skipjack tuna fisheries in the MZC.

2.6. Conclusion

Our findings show that biophysical variables affect the distribution of skipjack tuna catches in the MZC and that species distribution will be affected by climate change with potential implications on local and international fishing communities. This will be especially acute in the northern part of the MZC.

The model projected the distribution of skipjack tuna under optimistic (RCP2.6) and pessimistic (RCP8.5) climate change scenarios. The optimistic scenario projected that skipjack tuna catches would shift toward the southern part of Mozambique Channel, between latitudes 19ºS and 25ºS, by

2050, and that the distribution change would be either minor or unchanged from 2050 to 2100. In the worst-case scenario (RCP8.5) the potential fishing grounds were projected at latitudes >20ºS by 2050, and positive anomalies were projected to likely occur at latitudes < 20ºS between 2050 and 2100. By the end of the century, signs of high catch distributions are expected outside of the MZC at latitudes >25ºS toward temperate regions.

Given that climate change is projected to impact skipjack fisheries in the MZC this may lead to socioeconomic challenges for fishing communities. Coastal states in the MZC area should strengthen governance and promote policies to build resilience and increase the adaptive capacity of local, national and regional fisheries to reduce their vulnerability to climate impacts. The present study contributes to an understanding of the effects of of climate change by stakeholders and demonstrates a need to develop more participatory climate mitigation and adaptation strategies., It is suggested that adaptative co-management or inclusive MSP are supported to address uncertainty and connect knowledge with commitments that offer and develop alternatives to increase the resilience and adaptive capacity at both socio-ecological and socio-economic scales.

Acknowledgements

Special thanks to WIOMSA for a supporting productivity grant (MARG II Contract 3/2019). This study was partly funded by a PhD scholarship from the World-Wide Funding (WWF, Agreement #R27) to the first author to carry out his study at the University of Alicante (Spain). The acknowledgement is extending to Dr Jack Littlepage, Emeritus Professor from University of Victoria (Victoria Canada) for Technical English Language review provide to this article

Chapter 3: Socio-ecological and economic aspects of tropical tuna fisheries in the Mozambique Channel - Insight from Mozambique

3.1. Abstract

Industrial and small-scale tuna fisheries in Mozambique may compete over the same resources, which has potential socio-ecological impacts. The two types of fisheries were investigated by characterizing their catch trends, types of interactions, number of people they employ and revenues. Commercial landings, logbook data, and all previously established tuna Fishing Partner Agreements in the country were analyzed, as well as data collected from interviews with small-scale fishers. A declining trend in catches has been observed in the industrial fisheries sector, which has also been perceived by small-scale fishers, and suggests that there is some competition between these two sectors for the same tuna stocks, even when these stocks are targeted in separate grounds. Whereas the small-scale tuna fisheries sector provides thousands of local direct and indirect jobs and high economic benefits for fishing communities, the industrial fisheries sector may be more economically advantageous to Mozambique, if Fishing Partner Agreements are improved and enforced efficiently. Although maintaining non-overlapping fishing grounds between industrial and small-scale fisheries may be positive for the fishers, it could also be a cause of major stress for the tuna, which are exploited relentlessly.

Keywords: *Purse seine tuna fisheries, small-scale tuna fisheries, fleet interactions, shared stocks, Western Indian Ocean fisheries*

3.2. Introduction

The story of how tuna fishing in Mozambique began starts in the second half of the 1970s, when the Soviet Union began a research program on large pelagic fish (Simões, 1984a) using a drifting longline to map the space use and seasonality of tuna schools. In 1983, chartered vessels from Cape Verde began experimental fishing with pole and lines and live bait (Simões, 1984b). Results from both the Soviet Union research and the experimental fishing were promising. Consequently, between the end of 1983 and the beginning of 1984 Mozambique issued commercial fishing licenses to EU vessels (Simões, 1984b), thus following the path of other developing countries who placed tuna exploitation in the hands of international fleets through environmentally and socioeconomically dubious fishing agreements (Havice and Reed, 2012).

The first fishing partner agreement (FPAs) between the European Commission (EC) and Mozambique was signed in 1987 (EC, 1987). Authorized European vessels were subjected to pay the Mozambique authority fishing license fees, equivalent to 1,000.00 European Currency Units (ECU, i.e., 1 ECU is equivalent to1€), for the right to catch 50 tonnes of tuna in waters under the jurisdiction of Mozambique (EC, 1987). This first fishing agreement was terminated in 1993 by the Mozambican authority, who deemed that the agreement was disadvantageous toward the development of the local fishing sector (EC, 2003).

In 1999, the EC resumed conversations with Mozambique on tuna fishing and led to the drafting of a second agreement, which was implemented in 2004 for a period of three years with. fishing license fees was set at €3,000.00 for tuna seiners and €1,500.00 for long liners, corresponding to 120 tonnes and 60 tonnes of tuna, respectively. An updated third agreement, which renewed the protocol, was established between 2007 and 2011, and licence fees were set at €4,200.00 equivalent to 120 tonnes for tuna seiners and €3,500.00 equivalent to 100 tonnes for longliners.

The second and third agreements were apparently satisfactory for Mozambique given that after the agreements were up a fourth one came into force in 2012 for another three years. The fourth agreement included compensatory fees to develop the fishery sector, and details of who should pay for the logistical expenses of having scientific observers onboard (whose presence had been a requirement since the first agreement), in addition to stipulating an increases in licensing fees (purse seiners: €5,100.00 for 146 tonnes, longliners: €4,100.00 for 118 tonnes) (EC, 2012). This agreement was renewed in 2015, however licenses were mostly limited to longline vessels (>25), with less than 10 licenses issued to purse seiners (Chacate and Mutombe, 2018). A fact, since 2018 Mozambique has not issued licenses to purse seiners, as the country seeks to negotiate more profitable fees with international industrial tuna fisheries.

Despite the existence of fishing agreements since 1987, which established fees per tonne of fish caught, Mozambique only began recording national fisheries statistics in 2005 and these statistics are limited to total annual catches (www.mimaip.gov.mz). The update and renewal of consecutive agreements did not necessarily mean that the terms were fully met. For example, in Mozambique, jobs are rarely documented and benefits are mostly limited to fishing license fees (Afonso et al., 2017), in the other Western Indian Ocean (WIO) countries (e.g.: Seychelles, Mauritius, and Maldives) EU purse seine fleets generate more than 4000 jobs, corresponding to estimated economic benefits of between €22 and €40 million in 2014 (POSEIDON et al., 2014).

Although industrial tuna fisheries do generate some jobs in Mozambique, most of the fishing-related jobs in Mozambique are related to the small-scale fisheries (SSFs) sector, which does not follow any sort of agreement. For example, in 2012, almost 37,200 licenses were issued for SSFs with about 130,000 fishers directly involved in catching tuna (neritic and tropical tuna) and tuna-like species (Chacate and Mutombe, 2018).. As is the case with industrial fisheries, tuna SSFs also suffer from a lack of statistical information and sampling programs to record catch and effort data.

The situation is even worse when it comes to information surrounding the socioeconomic aspects of SSFs, and existing knowledge is either merely pertaining to anecdotes or only available in the grey literature.

Given that an overall picture of the social-ecological impacts of tuna fisheries is still lacking in Mozambique, this study describes the interactions between the industrial fisheries and SSFs sectors in coastal waters. For example, it is clear that SSFs target the same tuna stocks as industrial fisheries (i.e., tuna are highly migratory species), but due to the technological limitations of this type of fisheries, the grounds are closer to the coast (Ruttan et al., 2009), which by law (<12 nm) are not accessible to industrial fisheries (Mozambique Fisheries Law nº 22/2013). Whether these limits are enforced or not is not known. Given that tuna stocks are shared, both types of fisheries are expected to feel the effects of stock declines in the event of overexploitation or other causes (e.g., natural fluctuations, climate change). The extent of job creation by each fishing sector is also unknown in Mozambique. Thus, to fill these information gaps, data from industrial purse seine catches in Mozambique's Exclusive Economic Zone (EEZ) obtained from external databases were combined with career-history interviews with small-scale fishers. This information will contribute to improving the scientific knowledge surrounding tuna fishing. Additional and better knowledge can contribute to supporting a revision of the FPAs and assessing the trade-offs between Mozambique and foreign industrial fleets by using a precautionary approach to solve some of the pitfalls in how tuna fisheries are managed in Mozambique.

3.3 Methodology

3.3.1. Study location

The Mozambican coast is located on the west side of the Mozambique Channel (Figure 3.1). In this area, both industrial and small-scale fisheries target different species of tropical tuna. These include Katsuwonus pelamis (Linnaeus, 1758; skipjack tuna - SKJ), Thunnus albacares (Bonnaterre, 1788; yellowfin tuna - YFT), and Thunnus obesus (Lowe, 1839; bigeye tuna - BET). Foreign industrial distant-water fleets harvest tuna with the use of hand lines, longlines and purse seine gears. According to data provided by the Spanish Oceanographic Institute (IEO) and the Indian Ocean Tuna Commission (IOTC), the main tuna fishing grounds in Mozambican waters for purse seiners extend primarily from the centre to the northern part of the country (latitude <20S) (Figure 3.1). Data retrieved from IEO correspond to the logbook records of Spanish purse seine fleets, whereas data gathered from IOTC include all data from purse seine fleets who have FPAs with Mozambique (e.g., EU, the Seychelles, Mauritius, the Mayotte Islands, among others).

Thus, to access the eventual socioeconomic impacts of both the industrial and small-scale fisheries sectors sharing the same stocks, small-scale fishers were interviewed in four provinces: Cabo Delgado - Region A (northernmost villages from Palma, Mocimboa da Praia, and Ibo Island), Nampula – Region B (center-north villages in Memba, Nacala, and Mozambique Island), and Inhambane and Maputo provinces – Region C (southernmost villages in Inhassoro, Tofo Beach and Inhaca Island) (Figure 3.1). In all the villages studied, fishing is carried out with row canoes or wooden and fibre sailboats that are rowed, propelled or equipped with a small outboard engine of 15-50 HP. The gears used are mainly hook-and-line (with sardines used as dead bait), gillnets, and small manually-operated purse seines. The fish caught by small-scale fishers are either traded locally or kept for self-consumption, thus supporting local food security and livelihoods.

The coastal zones in Mozambique are characterized by a tropical climate with two marked seasons (Hoguane, 2007): a wet season, from November to April, and a dry season, from May to October. The wet season is related to the summer monsoon, whereas the dry season is linked to the winter monsoon, and the precipitation peaks are timed to the transition monsoon (Hastenrath, 2015). The tuna fishing season, for both SSFs and industrial fisheries, is very seasonal and typically begins in late February (wet season) and ends around the beginning of July (dry season) (Campling, 2012, Obura et al., 2018; Chassot et al., 2019).

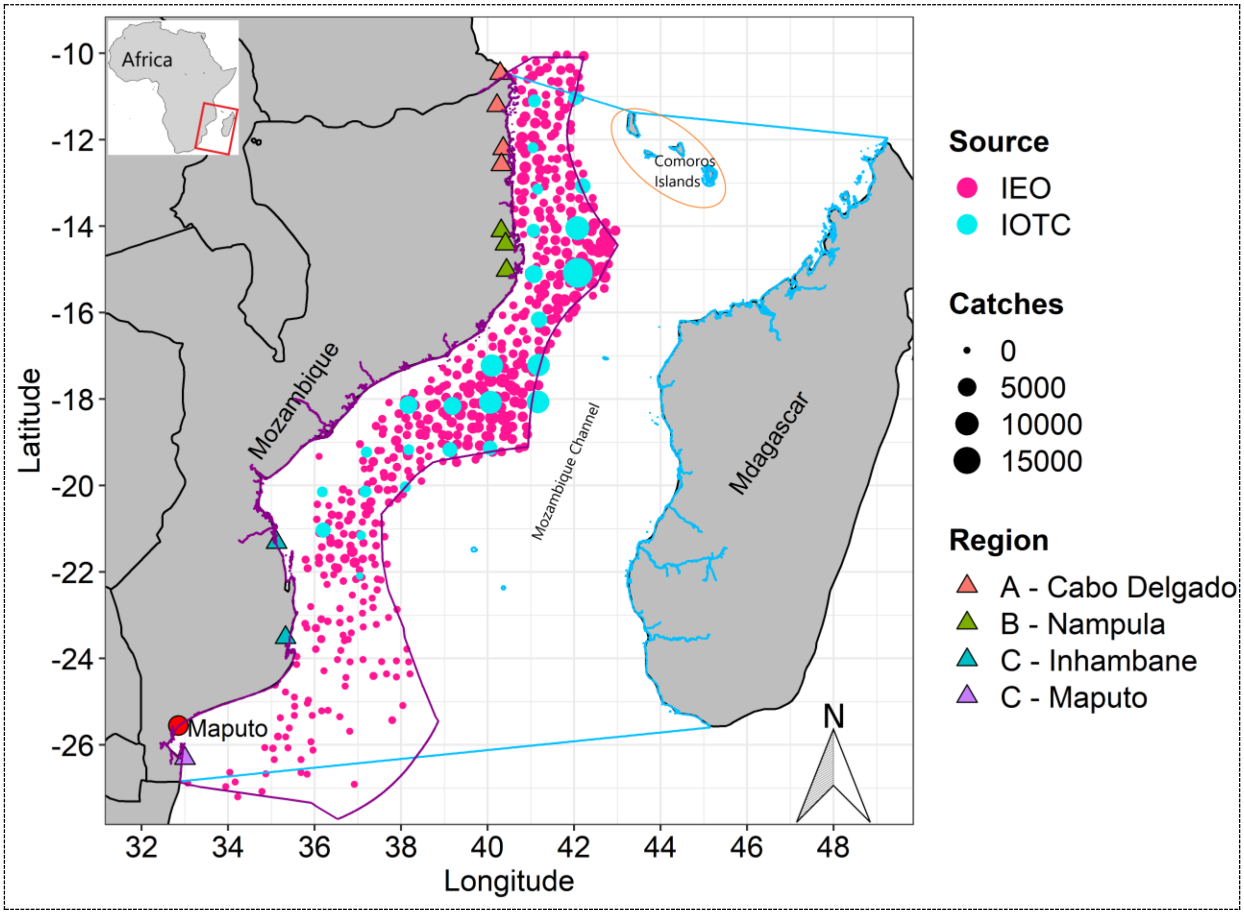


Figure 3.1. Map of the study area showing the distribution of tropical tuna (circles) catches, in tonnes by industrial purse seine fisheries, in the Mozambique Economic Exclusive Zone (delimited by the magenta line), as part of the Mozambique Channel (area delimited by the deep sky-blue line) for the period 1983 to 2014. Data were spatially aggregated as the sum of a 1/4º grid cell. The triangles mark the coastal villages in each region (A, B and C) where interviews with small-scale fishers and fishing authorities took place. Catches correspond to the tropical tuna species (SKJ - Katsuwonus pelamis, YFT- Thunnus albacares, and BET - Thunnus obesus). IEO logbook data refers to purse seine Spanish fleet fishing. IOTC (purse seine fleets from the EU, the Seychelles, and Mauritius, among others) for commercial data was gathered from all purse seine fleets that fished in Mozambican waters during study period. Shapefiles for Mozambique EEZ and the Mozambique Channel were accessed from https://www.marineregions.org. The red dot in the southern coast of Mozambique indicates Maputo, the country’s capital.

3.2.2 Data Collection

3.2.2.1 Macro-scale data from purse seine tuna fishing

Total landing commercial data were retrieved from the Indian Ocean Tuna Commission (IOTC) (www.iotc.org), the tuna regional fisheries management organization for the Indian Ocean convention area. These catch data were stored monthly over the period between 1983 and 2014 at a 1º x 1º spatial resolution in a database for the FAO fishing zone 51. In addition to catches per species, the data file also included information on fleet, fishing grounds, date (year and month), fishing hours and, in the case of purse seiners, and set type (i.e., whether fishing was conducted on Free Swimming Schools -FSC or on Fish Aggregating Devices -FAD – any type of floating object used to aggregate tuna). Furthermore, daily sets from logbook data for Spanish purse seiners covering the same spatial and temporal resolution were provided by the Instituto Español de Oceanografía (IEO) and were used to compare and complement tuna catch trends. The logbook data were more representative because they were collected through a scientific sampling observation programme carried out by the IEO. Logbook data also included information on catches per species and fishing mode (FSC and FAD), fishing hours, date (year, month, and day of the fishing operation), and location of the fishing activity (i.e., longitude and latitude), and the fishing sets were aggregated as the sum of ¼º resolution. To estimate the Catch Per Unit Effort (CPUE), total catch per year was divided by total fishing hours.

To describe the socio-economic issues facing tuna fisheries over the last three decades on a macro-scale, publications from the Mozambique Ministry of Fisheries Authority database (www.mimaip.gov.mz) were revised and available data were retrieved from the European Union database (www.eu.org) to access the Fisheries Partnership Agreements (FPAs) between Mozambique and the EU. Both peer-reviewed (e.g., Chassot et al., 2019) and grey literature, including technical and project reports about the socio-economic aspects of fisheries in

Mozambique were also reviewed (e.g., Gorez, 2003; EC, 2007; Kusi, 2008; EC, 2012; POSEIDON et al., 2014; Afonso et al., 2017; Lecomte et al., 2017a; Lecomte et al., 2017b; Mutombene et al., 2017; Chacate and Mutombe, 2018), together with dissertations (e.g., Otterlei, 2011; MANACH, 2014; Mendiate, 2016; Augustave, 2018). Revenue data were extracted from the FPAs. Nevertheless, information regarding job creation for Mozambicans within industrial tuna fisheries segments (extractive, transhipment to processing) was hardly found.

3.2.2.2 Interviews with small-scale fishers

Interviews with small-scale fishers were carried out between 2017 and 2018 in 10 villages in three different regions along the Mozambique coast (Figure 3.1). Additionally, the provincial and local fishing authorities in each village were contacted both during the scooping phase and throughout the course of the research to discuss the data gathered from fishers. During the scooping phase it emerged those small-scale fishers mostly target tuna in the northern and southern parts of the Mozambique coast, but rarely in the central region. Therefore, the study design included seven villages in the north (10ºS - 15ºS), three villages in the south (21ºS - 26ºS), and no sampling in the centre, between 15ºS and 21ºS (Figure 3.1).

In the villages, a semi-structured face-to-face questionnaire was applied, given that this method allows flexible and interactive discussions between the interviewer and interviewees (Babbie, 2012; Johannes et al., 2000; Wengraf, 2001). The questionnaire had four parts (Supplementary material C): personal information (e.g., age, experience, and education), tropical tuna catches (e.g., size composition of catches, seasonality, gear types, fishing equipment and techniques), socioeconomic aspects of tuna fishing (e.g., revenue, employments, value chain, fishing cost), and interactions between SSFs and industrial purse fisheries (e.g., types of interactions, use of FADs, potential impacts).

Methods for this study included a combination of expert-opinion surveys, key informant interviews, and snowball sampling as per recommendations from previous authors (e.g., Huntington, 2000; McGoodwin, 2001). Expert opinion surveys are data collection technique in which the community council selects the most knowledgeable or experienced people in the village from a pool of potential participants to be interviewed by the researcher (Huntington, 2000). In the case of this study, whenever applicable, the community helped identify key informants, who were those that had more specific and detailed information on the catch of tropical tuna (Tremblay, 1957; McGoodwin, 2001). Each interviewee suggested the names of other local experts, which is a method known as "snowball sampling" (Huntington, 2000; McGoodwin, 2001). This sampling method was especially efficient given that less than 10% of the fishers in each study village target tropical tuna. Furthermore, fishing authorities, village leaders, and key informants were initially consulted to recommend expert tuna fishers who might be available to be interviewed, given the lack of official fisher databases in both the villages and at higher levels.

The interviews were either conducted at fish landing sites or at fishers' homes. Prior to beginning the survey, fishers were explained about both the goals of the research and what was expected of them. Only fishers with a minimum of 5 years of experience targeting tuna were approached. Interviewees were also explained that they had an option to participate or not, to leave the interview at any moment, or not to respond to specific questions. The interview proceeded after oral consent was obtained from the interviewee. The best times to conduct interviews were after fishers had finished their daily routines, when they were relaxing or repairing their nets, or during their days off in their villages. Local fishing leaders (i.e., the head of the local fishing council) were approached first in each of the study fishing villages to authorize the survey and to help identify potential experienced tuna fishers. Prior to applying the questionnaire, fishers were asked to freely talk about "good and bad" days of tuna fishing, both from the present and past. Only after this moment were fishers shown printed colour pictures and leaflets of the three tropical tuna species to make sure they were correctly identifying the species and the ones they have targeted. The interviews proceeded after it was confirmed that the fisher being interviewed had caught at least one of the three species shown. A technician representing the fishing authority and leaders of the community fishing council helped ensure the trust and collaboration of fishers for the interviews, which lasted, on average, 25 to 35 minutes.

A total of 101 fishers were interviewed, aged between 19 and 73 years old (41 ± 12, >32% between 41 and 50 years old), and who had been fishing for 5 to 55 years (21± 12, 80% ≥ 10 years of experience) (Figure S8, Supp. A). For overall interviewed, 33 fishers were from region A (fishing mode: 9 gillnetters, 14 hand liners and 10 small seiners), 35 from region B (being 5 gillnetters, 10 hand liners and 20 small seiners), and 33 fishers from region C all of them operating handline gears. The literacy level of the interviewees was low, with 91.4% either illiterate or with less than four years of schooling. Contrary to industrial fishers, small-scale fishers rarely focus on a single species or even group of species, such as tunas.

3.3. Data analysis

Macro-scale industrial purse seine data from the Mozambique EEZ were gathered from each database using the QGIS 3.4 software (QGIS Development Team, 2018), aggregated to a ¼º x ¼º spatial resolution, and exported as a *csv* file for posterior statistical analyses in the R statistical software (R Core Team, 2018). The packages ‘ggplot2’ (Wickham, 2009), ‘mgcv’ (Wood, 2006), and ‘polynorm’ (Venables et al., 2016) were used to view and model fleet behaviour, tuna catch trends and CPUE. Three-degree polynomial order regressions were used, as they provided the best statistical score of goodness-of-fit (r^2) for catch trends for both logbook and commercial data. The number of people employed in fisheries and total revenues were the main social and economic indicators, respectively, for descriptive approaches of industrial fisheries.

With respect to SSFs data, it was investigated whether the largest tuna (kg) ever caught or seen (i.e., caught by another fisher) by fishers had changed over time, according to their own recollections of the size and year when the catch occurred (Tesfamichael et al., 2014). ‘Largest individual tuna’ was chosen as the ecological indicator to be recalled by fishers because tropical tuna species are often mixed with other species, including both pelagic and neritic tunas, thus hampering fishers’ abilities to understand best catches for only tropical tuna species. Referring to fisher memories is a relatively reliable strategy to estimate changes in catches (amounts and fish size) when official statistics are not available (Damasio et al., 2015). Again, polynomial regressions were used to analyse catch trends, specifically the relationship between the largest tuna ever caught and the year of occurrence.

Villages were also aggregated into regions in order to access the environmental and local perceptions of fishers toward the social and economic impacts of tuna fishing in their villages. Fishers from close villages were assumed to share similar marine environments and, therefore it was assumed that people living in these villages shared similar adaptation strategies, specific behaviour, fishing cultures and self-organization arrangements rooted in the exploitation of that particular environment (McGoodwin, 2001). F-tests were applied to compare the variability of reported means for species frequently caught by fishers per month among regions (Underwood, 1997). Similar to the SSFs sectors in other regions throughout the world (McGoodwin, 2001), it is not easy to distinguish subsistence from commercially oriented fishing in the study villages. Thus, interviewees were clustered by gear types to allow comparisons among gear types within and among regions. Like the macro-scale descriptive analyses, the number of people employed and revenues were the main social and economic indicators considered. The monthly workload was converted into full-time equivalent jobs or employment (FTE). FTE is a unit of measurement of the average number of workers doing a specific task, in a way that makes them comparable, although they may work a different number of hours per week (ilostat.ilo.org). The unit was obtained by comparing the average working hours of the average crew using a specific type of gear (e.g., gillnet, handline or purse seine) to the average number of hours of a full-time worker in Mozambique (i.e., 1.0 FTE for a worker is equivalent to 8 hours / day x 5 days / week x 4 weeks / month ≈160 hours per month). For this study, one Mozambican full-time worker was compared to the average crew, rather than the individual, given that the result of the crew's work is collective, rather than individual, i.e., total fish landed.

Because of the heterogeneity and lack of archive information relative to investments and the operational costs of fishing within and among gear types, individual revenue was assumed to be the best economic indicator recalled by small-scale fishers. After fish caught on a trip are sold, the revenue is divided among the crew according to one of three arrangements: (i) *self-fisher* - there is only one fisher, who also owns the boat and thus pays the costs and keeps the entire revenue; (ii) *team fishers* - first the daily operational cost (e.g., fuel and oil) are subtracted from total revenues, when applicable, then 50% of the remaining revenues go to the fisher who owns the vessel, and the remaining 50% is shared equally among the crew (excluding the boat owner); and (iii) *patron* - the boat is owned by a patron, who keeps 40% of the revenue (after discounting the operational costs); the remaining 60% of the income goes to the actual fisher(s).

3.4 Results

3.4.1 Macro-scale purse seine tuna fisheries

Industrial purse seine fisheries have been targeting tuna in Mozambican waters since 1983 (Figure 3.2a). Prior to this period, catches were seldom reported, despite the fact that the Russians had been researching and fishing the Mozambican coast since the mid-1970s. Although Spain only began fishing in Mozambican waters two years after France, accounted for most of the catches during the study period (49% of the total accumulated catches over 30 years) (Figure 3.2). Between 1983 and 2014, Spain and France reported total accumulated catches of 58.1 and 37.2 thousand tonnes of tuna, respectively, whereas the regional fleets (e.g., Seychelles, Mauritius, Mayotte) together accounted for about 10.9 thousand tonnes, and overall the NEIPS fleets (Netherlands, Italy, Greece, Portugal, Japan, Korea, and others), accounted for almost 12.2 thousand tonnes (Figure 3.2b). Regardless of the fleet, the main target has been skipjack tuna (Figure 3.2b), which accounts for more than 65% of the total catch during the study period (YFT and BET at 29% and 5% of catches, respectively).

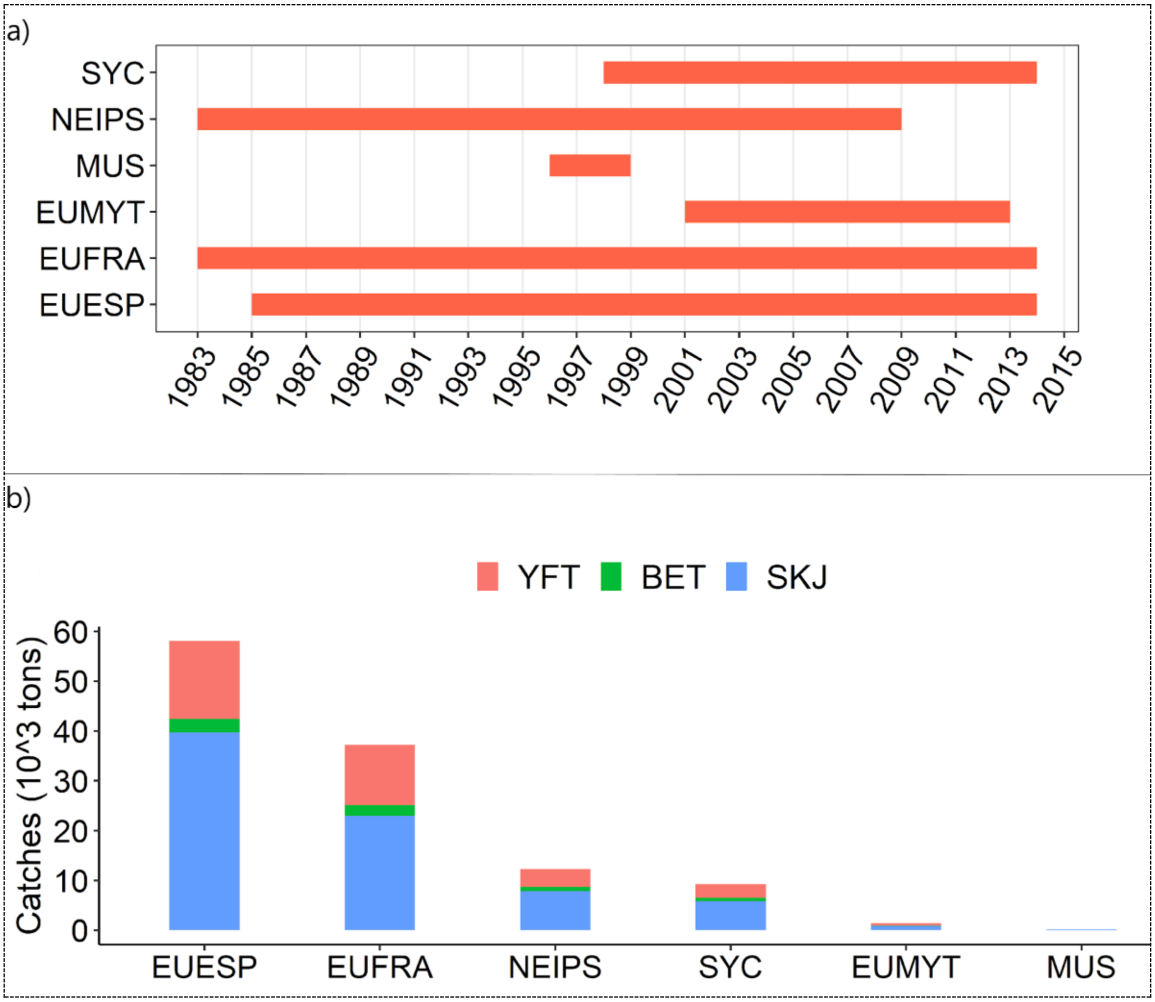


Figure 3.2. History of purse seine fleets operating in the Mozambican EEZ and targeting tropical tuna between 1983 and 2014 (a), and their respective total catches over time (b). All fleets are international: EUESP - Spanish, EUFRA - French, NEIPS - Other fleets, SYC - Seychelles, EUMYT- Mayotte Island French territory, and MUS - Mauritius fleets. BET- Bigeye tuna, SKJ - Skipjack, and YFT-Yellowfin tuna. There are no records of Mozambican purse seine fleets operating in the region.

The tuna catch trend is characterized by a semi-parabolic curve, regardless of the source of data (detailed Spanish logbook or general commercial data) (Figure 3.3). The Spanish purse seine logbook data shows catches increasing at a rate of 4.06% per year between 1983 and 2000, followed by a fast decline of 7.21% per year until 2014 (historical minimum). The overall purse seine commercial data shows a less pronounced annual increase and decrease, and the decline is shown to have occurred earlier than in the logbook data. In the latter data, catches are shown to have first increased at a rate of 1.65% per year between 1983 and 1997, and then to have decreased at a rate of about 1.35% until the end of the time series (which is also the historical minimum). Therefore, there is some evidence to suggest that catches have been generally declining over the last 15 to 20 years, however, there is a high degree of variability within each dataset, i.e., the logbook (r^2=0.51) and the commercial (r^2=0.45) data (Figure 3.3a-b). The CPUE showed growth rates of 13.33% and 6.41% for logbook (r^2 = 0.42) and commercial (r^2 = 0.14) data, respectively, between 1983 and 1998 (Figure 3.3 c-d), followed by some stability, and another increase in the last three years of the time series (Figure 3.3 c-d).

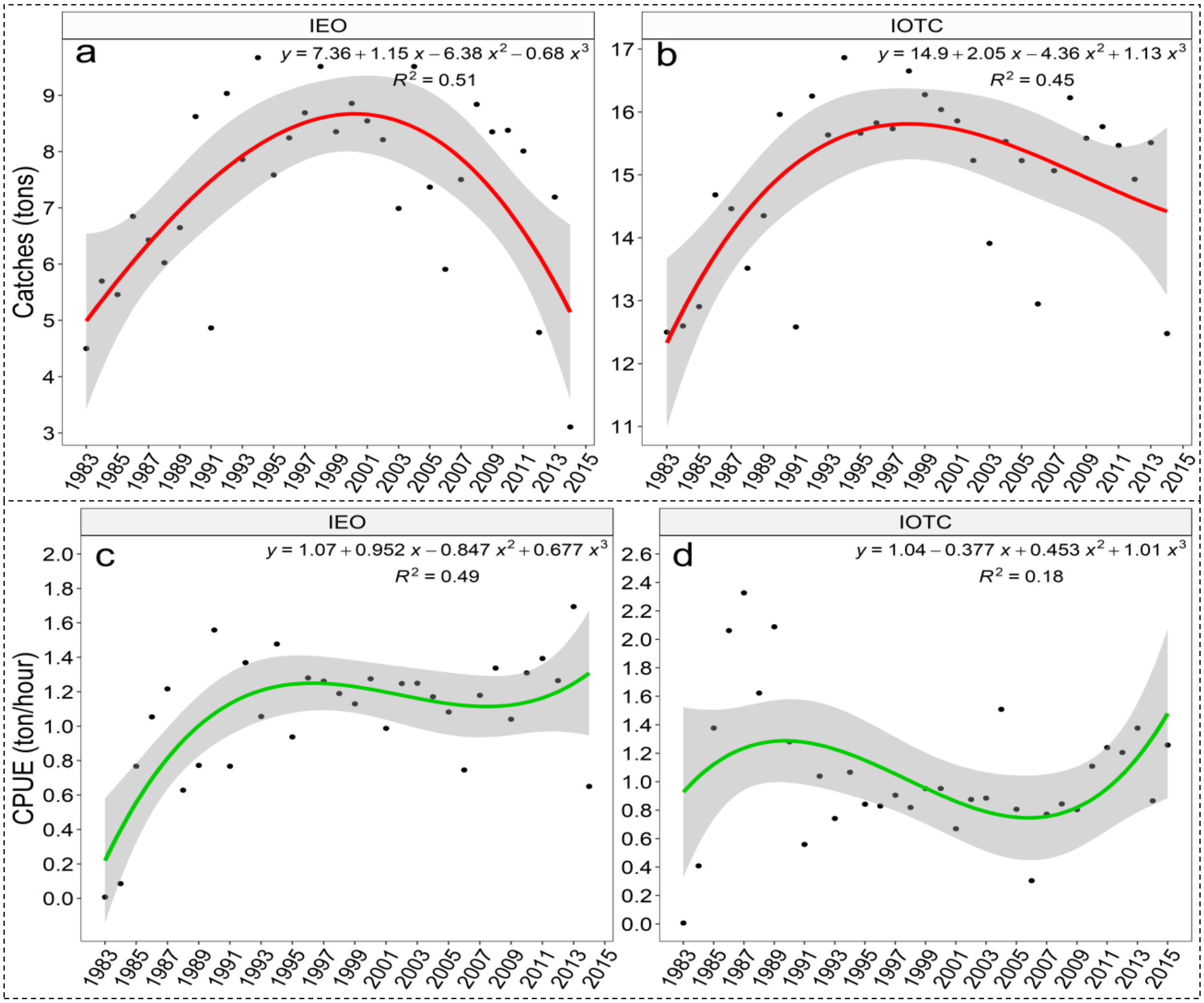


Figure 3.3 – Catch trends (a and b) and catch per unit of effort (CPUE) (c and d) by purse seine fleets in Mozambique for the period 1983 to 2014. Catches are composed by the following tropical tuna species: bigeye tuna (Thunnus obesus), skipjack tuna (Katsuwonus pelamis), and yellowfin tuna (Thunnus albacares). Logbook data provided by the Instituto Español de Oceanografia (IEO), and commercial data provided by both the Indian Ocean Tuna Commission (IOTC). Data were transformed to a logarithmic scale to reduce the variance in order to observe trend patterns

Revenues from purse seine fleets under the FPAs between Mozambique and the EU were summarized (Table 3.1). The contribution fees from the EU to develop the Mozambican fisheries sector improved with every consecutive FPA. For example, the FPAs approved in 2007 and 2012 reveal that the annual EU contributions to developing the fishing sector were €826,400 and €1,087,100, respectively (Table 3.1), which corresponded to ~ \$680,000 in 2007 and ~\$800,000 in 2012 PPP dollar value (PPP - purchasing power parity USD). The last fishing agreement expired in 2015 and to date has not been renewed.

Table 3.1- Revenue summary for purse seine fleet under fisheries partnership agreements (FPA) between Mozambique and the European Union. Data sources: https://ec.europa.eu/fisheries and https://www.iotc.org. mt = metric tonnes. All FPAs started on January 1st and ended on December 31st.

Item	**Fishing partnership agreements signed**					
Year of FPA signature	**1987[1]**			**2003**	**2007**	**2012**
Protocol agreement	**Fist**	**Second**	**Third**			
Duration (Years)	3	2	13	3	4	4
Number of purse seine licenses issued[2]	40	44	42	35	42±7	21±3
FPA total contribution (10^3 €/year)	2.500	3.430	280	600	650	980
Accessing fees per vessel (€ after 2003)	-	-	-	3,000	4,200	5,100
Annual fees from license (10^3 €)	40	44	42	105	176.4±29.4	107.1±15.3
Shipowner contributions per mt (€)	20	20	20	25	35	35
Reference catches per licence fee (mt)	50	50	50	120	120	146
Total allowable catches (mt)			-	8,000	10,000	8,000

[1] The number of licenses issued under 1987 FPAs included purse seine and longline vessels

[2] Number of purse seine fleet also includes other non-European vessels

3.3.2. Knowledge of small-scale tuna fishers

The largest tuna size recalled (in kilograms) by fishers demonstrated a declining rate of about 2.5% per year (Figure 3.4). Most of the fishers interviewed reported that the largest tuna they had ever seen had been observed between 5 and 10 years prior to the reference years 2017 to 2018, when the interviews were conducted. When fisher responses were separated into two groups, those with up to 10 years of experience and those with more than 10 years of experience, the younger and less experienced fishers reported that the largest tuna they had ever caught or seen (average = 40 kg) had been caught 10 years prior to the interview (i.e., in 2008), whereas the older and more experienced fishers reported that the largest tuna they had ever caught or seen (60 to 75 kg) had been caught between 1975 and 1980. Given the modelling approach and the low number of samples at the beginning of the series, the declining rate seems to be more pronounced before 1995, followed by a flattening trend. Despite the relative declining rate between 1975 and 1995, followed by flattened trend, the largest tunas mentioned by fishers were two individuals weighing 100 kg each that was observed in 2008 and 2017, respectively, although the fitting curve shows dispersion of fisher's responses (Figure 3.4; $r^2 = 0.12$).

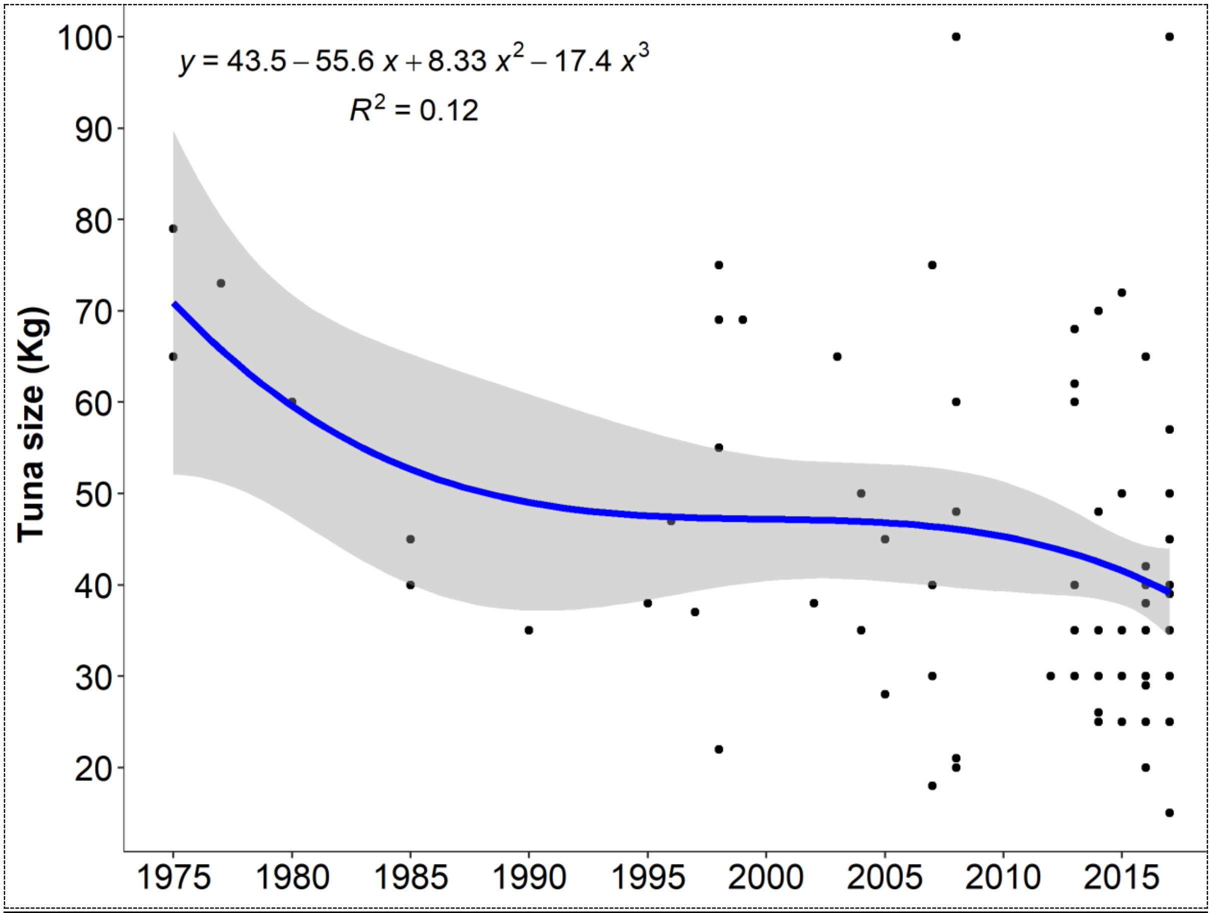


Figure 3.4 - Historical trend of the largest tuna ever recalled to have either been seen or caught by small-scale fishers.

.

The seasonality of tuna species occurrence, according to fishers, also varied according to the research region. Fishers reported a higher occurrence of tropical tuna from late December to May in areas A and B (northern region), whereas in area C (southern region) species were reported to be mostly caught between late June and November (Figure S9, Supp. A). In fact, the seasonality of fishing seems to be especially marked for skipjack, which is rarely caught between June and November in region A, becomes slightly more reported during this same period in region B, and then is said to be predominantly caught in this season in Region C (Figure S9, Supp. A). Both bigeye and yellowfin tuna are also absent between June and November in Region A, but present at similar rates, or even higher, in Regions B and C.

When fishers were asked about the average size (kg) of the tuna they normally catch, both bigeye (most catches between 5 Kg to 30 Kg) and skipjack tunas (between 1 and 7 kg) showed a positively skewed distribution, whereas yellowfin tuna (between 5 Kg to 30 Kg) followed a normal distribution (Figure S10, Supp. A). Fishers reported that they mostly target skipjack, which, according to 83% of the fishers interviewed, is the main species occurring in the area (Table 3.2). The occurrence of bigeye and yellowfin tuna, which were said to be usually caught as juveniles, were reported by 53% and 60% of the fishers, respectively (Table 3.2).

The average size reported for skipjack in region A was larger than the average size reported in the other regions (A x B: F=4.01, p-values= 0.0003; A x C: F= 2.84, p-value=0.0133) (Table 3.2). No difference was detected between regions B and C (F = 0.7077; p-value = 0.3527). For bigeye and yellowfin tuna the average size did not vary across regions: bigeye (A x B: F=1.45, p-values=0.2932; A x C: F= 0.80, p-value=0.7757; B x C: F=0.45, p-value=0.1117), and yellowfin (A x B: F=1.95, p-values=0.2174; A x C: F= 0.77, p-value=0.5993; B x C: F=0.40, p-value=0.07305).

Over the last 5 to 10 years prior to 2017-2018, 65% (*n=101*) of the fishers interviewed perceived a decline in tuna occurrence. This was especially marked in region C, where 88% of the fishers interviewed claimed to have noticed this decline. By contrast, only 50% of the fishers interviewed in the other two regions claimed to have noticed this decline (Table 3.2). Despite the reported declines, most interviewees in region A (64%) still considered it easy to catch tuna, according to their fishing experience, gear used, and season. By contrast, in regions B and C, almost 63% of the fishers suggested that it was difficult to catch tuna due to either a lack of technologies or scarcity of tuna (Table 3.2). The vast majority of fishers (~85%) claimed that tunas are mostly caught at sunrise and sunset (Table 3.2).

Table 3.2 - Summary of the interview data related to changes in tuna catches, and interactions with industrial fleets. A, B and C indicate regions of clustered sampled villages. SKJ-skipjack, BET- bigeye tuna, YFT- yellowfin tuna, FAD- fishing aggregating device. Percentage values in brackets in rows of boat size correspond to the number of respondents.

Item	**Category**	**Sampling regions**			**Overall (n=101)**
		A (=33)	**B (n=35)**	**C (n=33)**	
Tuna species average size (kg) (% in brackets referrers to the number of fishers who reported each species per region)	SKJ	7.64 ±4.39 (76%)	4.15 ±2.19 (97%)	6.12 ±2.60 (76%)	5.77±3.41 (83%)
	BET	18.07 ±7.04 (42%)	16.19 ±4.73 (60%)	19.42 ±6.67 (56%)	17.81±6.14 (53%)
	YFT	22.82 ±8.36 (52%)	19.27 ±5.99 (42%)	16.82 ±9.51 (85%)	19.13±8.68 (60%)
Number of fishers 5 years before 2017/2018 (%)	Increased	55	63	70	62
	Did not change	33	29	6	23
	Decreased	12	8	24	15
Perceived trend of tuna abundance over the last 5-10 years before 2017 (%)	Increased	45	46	12	35
	Decreased	55	54	88	65
Has it been easy to catch tuna over the last 2 years (%)	Yes	64	37	36	54
	No	36	63	64	46
Best period of the day to catch tuna (%)	Sunrise and Sunset	85	86	85	85
	No difference	15	14	15	15
Have previously seen industrial vessels in their fishing sites (%)?	Yes	24	6	42	24
	No	76	94	58	76
Have previously seen or used FADs (%)?	No	100	100	100	100
Average Fishing Time	Hours per day	6.70±3.19	6.77±3.28	5.94±2.41	6.48±3.01
	Day per month	19±3	20±3	15±4	18±4
Boat size (m)	Engine	4-11 (33%)	8-12 (57%)	3.5-7 (79%)	3.5-12 (57%)
	Sail and rowing	2 -8.5 (67%)	3-10 (43%)	3-6 m (21%)	2.5 -11 (44%)

3.3.3 Socioeconomic aspects of small-scale tuna fisheries

The three regions differed in the proportion of gears used (Table 3.3). In region A, hand lines predominate (45.5% versus 30.3% small seine and 24.2% gillnets), whereas in Region B small seines are used by the majority of fishers (57% versus 29% hand line and 14% gillnets), and in Region C, in the south, only hand lines are used.

The distribution of gears and how they are used across regions also affects the number of people employed in each place. For example, the crew sizes of boats that operate gillnets in Region A range from 4 to 20 fishers per vessel, compared to 6 to 17 people per vessel in Region B according to the boat and gear sizes. The average daily working time for gillnet fishers is ~11 hours in both regions A and B, and approximately 17 to 19 average days per month. Therefore, the monthly average working loads were estimated at 14.2 ±0.3 and 15.1 ±0.2 FTE jobs for areas A and B, respectively (Table 3.3).

With respect to handline fishers, the average crew size is 3 ± 2 and 5 ± 2, and ranges from 1-7 in regions A and C, while in the villages visited in region B, fishers worked alone. The average working time for handline fishers was around 10 hours per day for all three of the visited areas. Handline fishers declared an average of 21 fishing days per month in areas A and B, while in region C the declared average was about 15±4 days per month. Hence, the monthly workloads for handline fishers were set to 3.89 ± 0.7, 1.3 ± 0.3, and 5.1 ± 4.99 FTE jobs in the villages in areas A, B, and C, respectively (Table 3.3). Compared to the normal working hours of the average worker in the country, the monthly working hours are relatively higher in areas A and C and, close to the average in area B, because in area B fishers mostly work alone.

On average, small seines provide more jobs than the other gears (26 ± 6 and 23 ± 9 fishers in region A and B, respectively). The working load for seiners is about 12 hours per day in villages in region A, and 11 hours in villages in region B, with working days set to an average of 18±3 and 20

±3 in region A and B, respectively. Hence, compared to a full-time employee, the monthly workload was found to be 34.4 ±12.3 FTE jobs in region A, and 32.9 ±22.1 FTE in region B (Table 3.3). This is the highest workload among all previously described fisher groups, and >30 FTE times higher than the average monthly hours of an average worker.

In all the fishing villages evaluated, most fishers (>50%) have to invest to maintain their fishing, while less than 23% of fishers interviewed, i.e., those working for a patron, do not know who funds their fishing. Few fishers have been beneficiaries of any type of credit from different sources (e.g.: government subsidies, loan from NGO and bank) , although in region C this value reach 30.3% out of 33 (Table 3.3).

Gillnet fishers are remunerated based on a shared income team-fisher system (type *ii*) (Table 3.3). Overall, gillnet fishers in region A make 1,5 times more money than fishers in region B. Boat owners were only accessed in region B, and were found to make more than twice the amount that fishers make in the high season (December - May), and 82% of the average fisher income in the low season (June - November) (Table 3.3).

Small purse seiners are also arranged in a team-fishers system (type *ii*) and share fishing revenues (Table 3.3). In region A, boat owners earn, on average, about 1.5 times more than the fishers working for them. In region B a boat owner makes more than 2 times what fishers make in the high season and 89% of what fishers make in the low season. When regions are compared, boat owners from area A make 84% of the average income of boat owners in area B in the high season, and similar incomes in low season. The incomes of fishers, by contrast, were similar between regions A and B in the high season. In the low season, fishers from region A earn an average of 76% of what fishers in region B earn (Table 3.3). There were no fishers met operating small purse seine and gillnet in visited villages during the interviews in region C.

Hand line fishers are organized in three different income systems (Table 3.3). Fisher who are boat owners and patrons were only accessed in region C and were found to make about 3 times more money in the high season than in the low season. Regardless of the season, patrons make almost twice the amount earned by fishers who are boat-owners. In region A, independent fishers make 29% of the average crew fisher’s income in the low season, and 46% in high season, respectively (Table 3.3). Independent fishers in region A were found to make more than twice that of independent fishers in region B in the high season, and three times as much in the low season, respectively, whereas overall crew-member fishers in region C were found to make about 60% of the average fisher’s income in region A (Table 3.3).

Table 3.3- Summary of the socioeconomic aspects of small-scale tuna fisheries in Mozambique. A, B and C are the sampling village regions, and n is the sample size. FTE- full time equivalent jobs. The roman numbering i, ii, and iii indicates the types of revenue sharing: boat-owner (i) - fishers are also boat owners who pay for the costs and retain all the profits; team-fishers (ii)- 50% of the income for the patron, who is also a fisher, and the remaining is divided equally among the crew; patron (iii)-60% of the revenue is shared among the crew and 40% goes for the patron, who is not part of the crew. The % presented in brackets under the variable species prices corresponds to fishers who have been catching each species in the region. Incomes and prices were converted to euros and the reference year is the sampled year 2017 (https://ec.europa.eu/budget/graphs/inforeuro.html) as follows: 1 MZN (Mozambican currency) was equivalent to €0.0140025. December -May (Dec -May), which is high fishing season, and June - November (Jun - Nov), which is the low fishing season.

Item	**Category**	**Sampled fishing villages, clustered by region**		
		A (n=33)	**B (n=35)**	**C (n=33)**
Funding sources for fishing (%)	Credit	9.09	22.86	30.30
	Self-funded	75.76	54.29	60.61
	Unknown	15.15	22.86	9.09
Nº of interviewees	Gillnet	9	5	No fisher found in visited villages
Crew size - gillnets		12 ± 6	11 ± 4	
Daily working hours		11.38 ± 2.91	11.2 ± 1.47	
Fishing days		17 ± 2	19 ± 4	
FTE per month		14.20 ± 0.27	15.05 ± 0.16	
Forms of income sharing		ii	ii	
% Respondents on gillnets		24.24	14	
Boat-owner (Dec-May) €		-	793.48 ± 462.06	
Boat-owner (Jun -Nov) €		-	74.68 ± 40.15	
Fisher (Dec-May) €		371.07 ± 299.58	245.04 ± 35.01	
Fisher (Jun -Nov) €		120.77 ± 119.62	91.02 ± 21.00	
Boat size (meters)		5 - 10	4 - 7	
Nº of interviewees	Handline	14	10	33
Crew size - handline		3 ± 2	1 ± 0	5 ± 2
Daily working hours		10.36 ± 3.67	10 ± 2.61	10.88 ± 5.27
Fishing days		20 ± 3	21 ± 2	15 ± 4

FTE per month		3.89 ± 0.02	1.30 ± 0.27	5.10 ± 4.87
% Respondents on handlines		45.45	29	100
Forms of income sharing		ii and iii	ii and iii	i, ii and iii
Boat-owner (Dec-May) €		-	-	380.61 ± 239.71
Boat-owner (Jun -Nov) €		-	-	122.84 ± 79.40
Independent fisher (Dec-May) €		257.30 ± 266.50	106.57 ± 16.04	-
Independent fisher (Jun -Nov) €		87.52 ± 109.25	25.67 ± 11.43	-
Crew fisher (Dec-May) €		555.43 ± 431.79	-	346.93 ± 400.10
Crew fisher (Jun -Nov) €		303.39 ± 277.08	-	178.50 ± 244.70
Patron (Dec-May) €		-	-	644.12 ± 491.88
Patron (Jun -Nov) €		-	-	208.64 ± 117.19
Boat size (meters)		3 - 6	2.5 - 5	3 - 7
Nº of interviewee	Small purse seine	10	20	No fisher found in visited villages for the sampling period
Crew size – purse seine		26 ± 6	23 ± 9	
Daily working hours		12 ± 4.15	11 ± 4.32	
Fishing days		18 ± 3	20 ± 3	
FTE per month		34.44 ±12.34	32.93 ±22.14	
% Respondents on purse seine		30.30	57	
Forms of income sharing		ii	ii	
Boat-owner (Dec-May) €		455.08 ± 282.23	542.87 ± 325.53	
Boat-owner (Jun - Nov) €		117.27 ± 93.39	95.32 ± 82.82	
Fisher (Dec-May) €		280.08 ± 70.01	252.05 ± 224.74	
Fisher (Jun -Nov) €		80.51 ± 59.51	106.42 ± 123.22	
Boat size (meters)		8 -11	8 - 12	
Range of net income (€)	Dec-May	42.01 - 1,680.30	42.01 ± 1,400.25	42.00 ± 2,800.50
	Jun-Nov	14.00 - 840.15	14.00 ± 280.05	14.00 ± 1,050.19
Species price (€)	BET	1.24 ± 0.36 (42%)	1.16 ±0.33 (60%)	2.13 ± 0.59 (67%)
	SKJ	0.92 ± 0.29 (61%)	0.83 ±0.33 (100%)	1.84 ± 0.60 (85%)
	YFT	1.34 ± 0.40 (48%)	1.19 ± 0.32 (42%)	2.13 ± 0.43 (86%)
Tuna destination (%)	Market	100	100	49
Fisher satisfaction (%)	Satisfied	63.64	68.57	85.85
	Unsatisfied	9.09	11.43	15.15
	No comment	27.27	22.86	0

3.5. Discussion

Foreign purse seine tuna fleets, especially European fleets, have been fishing in Mozambican waters since the 1980s. Between that time and the 2000s, industrial purse seine tuna catches increased at a fast rate. This growth rate was influenced by a growing number of licences issued to European purse seine vessels, mainly from France and Spain (EC, 1987; Parks, 1991), which were equipped with advanced fishing technologies (Fonteneau et al., 2013; Lopez et al., 2014; Lopez and Scott, 2014; Torres-Irineo et al., 2014) that enabled an increased fishing effort (Figure S11, Supplementary Material A). After the 2000s, catches started to decline, in part because a number of fleet exiting the fisheries industry in response to high levels of piracy observed in the WIO (Chassot et al., 2012; Pillai, 2012). As a result, after the 2000s, fishing hours and catches per unit effort also declined (Figure S11, Supp. A). For example, in Mozambique about 51 purse seine vessels applied for licenses in 2007, whereas in 2014 this number dropped to 22 (Chacate and Mutombe, 2018). Despite regional and international efforts to secure the level of piracy in the Mozambique Channel (Pillai, 2012; Bergeron, 2014), to date the FPAs with the EU, which expired at the end of 2014, have not been renewed (Chassot et al., 2019). In addition to piracy, the FPA negotiations have been affected by a lack of agreement on transparency clauses that would allow Mozambique to improve its monitoring of catches by EU vessels in its waters (Davies and Markides, 2019). Apparently the government of Mozambique continues to negotiate sustainable (i.e., ecologically and socioeconomically sustainable) FPAs with foreign fleets, although the number of purse seiners fishing in domestic waters dropped to 8 in 2015 and to 4 in 2018 (Chacate and Mutombene, 2019). The lower number of industrial boats targeting tuna, however, is perhaps not the only reason why catches have declined. Factors such as overfishing (Campling, 2012) and changes in oceanographic conditions may have also played a role. Alarming oceanic warming (Popova et al., 2016) may induce climate change with implications on the seasonal migration and aggregation of target species (tropical tuna), which in Mozambique coast as part of Mozambique Channel are predicted to shift their aggregation in northern of the Channel toward south and temperate waters by the end of the century (Dueri et al., 2014;Marsac, 2017) or displaced elsewhere and moving to deep water in ocean Monllor-Hurtado et al., 2017), and ultimately may have implications on fleet behaviour and the strategies they adopt. On the other hand, even if stocks have declined, the CPUE has not shown clear signs of decrease yet. In both sources of purse-seine data used here, the CPUE has been relatively stable since the beginning of the 1990s, with a slight increasing trend in the last two to three years of the time series, possibly a result of fewer boats fishing Mozambican waters.

Although they are not affected by piracy, small-scale fishers also noticed a decline in tuna catches and perceived a decrease in the size of individual tunas (assessed here by the recollection of the largest tuna ever caught). Although small-scale and industrial fishers, in general, do not compete over the same fishing grounds (there is likely some competition happening in Region C – surprisingly the area where purse seine activity is lowest), they compete over the same stocks. Thus, if there were a real decrease in the tuna stocks exploited by foreign fleets, it would be natural to also observe this decline among local small-scale fishers closer to the coast (Hampton, 1991; Kleiber, 1991; Leroy et al., 2016). The fact that small-scale fishers noticed such a decline reinforces the hypothesis that the decline in industrial fisheries is not entirely due to fear of piracy. Indeed, recent IOTC assessments of yellowfin tuna have shown that this species is overfished, and that overfishing continues to occur (www.iotc.org). Other species, such as skipjack and bigeye tuna, seem to be in better conditions, however, the probability that skipjack is either overfished or that overfishing is occurring is close to 50% (www.iotc.org).

Overall, tuna stocks are harvested with a variety of gears (e.g., longlines, purse seines, pole -and-line, gillnets and handlines), both in the high seas (>12 nm) and in coastal waters (Lecomte et al., 2017; Mutombene et al., 2017; Chacate and Mutombe, 2018; Chassot et al., 2019). Additionally, fishers within the same category compete with one another, as is the case for small-scale fishers within a given region who compete to ensure their income and livelihoods. Nevertheless, the lack of data (e.g., tagging, species size and weight composition information) makes it difficult to elucidate and quantify the magnitude of interactions between fishing sectors and among fishers in the same sector (Kleiber, 1991; Leroy et al., 2016).

It is also worth highlighting that, despite the decreasing maximum weight observed by fishers with respect to the largest fish ever caught, a significant portion of small-scale fishers (<45%) consider that tuna populations have not been declining and that their decreasing catches are a consequence of limited technology. According to these fishers, if they had access to better gear, their catches would improve. Basically, these fishers would like to increase their effort and/or efficiency to make up for their growing losses, which is a strategy that many fisheries around the world turn to (Damasio et al., 2016). This strategy, often stimulated by governmental subsidies, is not only just a short-term solution, but also tends to worsen the stock situation (Sumaila et al., 2010; Sumaila et al., 2016). This misunderstanding of the causes behind stock depletion and the lack of capacity to find alternative resources to make up for decreasing incomes (e.g., access to better markets) are related to multiple factors, including the literacy barrier. Cognitive limitations due to poor or limited education can hinder fishers' access to financial credits, economic diversification, and access to market information that would allow them to negotiate better contracts for fish products with quality standards (Fatunla, 1997; McGoodwin, 2001; Maddox, 2007).

Although the EU, NEIPS, and regional purse seines fleets have brought some economic benefits to Mozambique, mostly in the form of fees paid to the government, they had limited impacts on different socioeconomic levels. For example, between 2006 and 2017, the average annual contribution from foreign industrial tuna fleets to the national fisheries sectors was about 18% of €2.95±1.02 million, gathered from overall fisheries licencing fees (Afonso et al., 2017). Other African and developing coastal countries have used fishing agreements to strength their governance, by improving the sustainability and profitability of their accords with the developed world (Barclay and Cartwright, 2007; Mailu et al., 2015). Countries such as the Seychelles, Mauritius, and Madagascar have, for instance, demanded national prioritization of port transhipments and tuna and by-catches species landings, employment of national fishers, establishment of fish processing units, and the development of a national industrial tuna fleet (Lecomte et al., 2017b). Canneries alone, which were established to process tuna purse seine catches, generated about €5.6, €56.32, and €76.05 million for Madagascar, Seychelles and Mauritius in 2016, respectively (Lecomte et al., 2017b), whereas Mozambique, in that same year made about €0.65 million (93% from tuna licensing fees), about 7% of which was from tuna added value products (Afonso et al., 2017).

In port states where tuna is transhipped there can be multiple benefits, extending from social (e.g., jobs and food supply) to economic benefits (profits), along the fisheries referral chain, as observed, for example, in Tuvalu, Salomon Islands, and Marshall Island (Barclay and Cartwright, 2007; James et al., 2018), and some WIO region countries (e.g., Maldives, Seychelles, Mauritius, Madagascar, etc.) (Lecomte et al., 2017). A decree (nº 74/2013) published in 2013 by the Mozambican government (Ministers-Council, 2017) is yet to be enforced, but it could potentially improve local socioeconomic conditions by demanding that transhipments, landings, and fish processing take place in the country. This decree is also expected to enforce the demand for scientific observers onboard, data collection systems, and the employment of Mozambican citizens on international boats; aspects that were required, but not fulfilled, in previous FPAs.

If well implemented, the benefits of agreements could offset some of the current loss of FTE jobs (e.g., one or two weeks without fishing per month) among small-scale fishers due to adverse oceanic coastal environmental conditions for fishing, and improve statistical data. Currently, Mozambique has been following the path of other developing tropical small-scale fisheries (Fatunla, 1997; Pauly, 1997), whereby its catches are landed out of urban centres and markets and without the use of official national ports. If industrial tuna fisheries were to tranship and land their fish products in national ports, these additional jobs could be occupied by the family members of fishers without interfering much in the dynamics of SSF villages. This already happens, for example, with industrial shrimp fisheries (Santos, 2007). Similar positive socioeconomic interactions have also been noted between industrial tuna fleets and SSFs in some of the Pacific Islands, specifically in Tuvalu (James et al., 2018).

Furthermore, besides the socioeconomic impacts, FPAs between distant water nations and other some African nations have been criticized for potential overfishing (Nagel and Gray, 2012; Augustave, 2018), and for either a lack or inconsistent fisheries data collection and reporting to IOTC for stock assessment and management advice, which adds significant uncertainty to the degree of stock exploitation (Otterlei, 2011; IOTC, 2018). However, the IOTC's most recent assessments of skipjack and bigeye tuna stocks indicated that these species are determined to be not overfished and not subject to overfishing, although important concerns were raised about yellowfin tuna, which was determined to be overfished, with overfishing still occurring (Lecomte et al., 2017a; IOTC, 2018; Davies and Markides, 2019). Proposals to adopt sustainable fishing partnership agreements (SFPA) have been discussed in the literature, and they include the protocols, provisions and recommendations by the IOTC (e.g., IOTC, Resolutions: 17/01; 18/01 and 19/01) on tuna and tuna-like species (Augustave, 2018; Davies and Markides, 2019). Despite the fact that several coastal states have tried to follow the IOTC recommendations, the SFPAs have been hampered by the difficulty of competing with subsidized tuna fleets (Grynberg, 2003; Arthur et al., 2019; Davies and Markides, 2019). For example, fisheries subsidies maintain the overfishing of yellowfin tuna in the WIO region, which includes the Mozambique Channel, which would be unprofitable otherwise (Arthur et al., 2019). Mozambique is one of the developing states where tuna fishing is carried out by subsidized foreign industrial fleets with FPAs access (Grynberg, 2003; Arthur et al., 2019), whereas local SSFs are subsidized by microcredits provided by the national government (Benkenstein, 2013).

The socioecological interactions observed in this study, in locations where industrial fleets and SSFs compete over the same stocks, have been reported elsewhere (Kleiber, 1991; Hampton, 1991). In Mozambique, specifically, there has been an attempt to regulate this competition by geographically separating the activities (as per the national fisheries law nº 23/2013) and by limiting

SSFs to up to 12 nm, where the industrial fisheries jurisdiction begins. Industrial purse seine fleets seem to monitor and manage their FADs efficiently (Soto et al., 2016), by controlling them from drifting toward SSF areas and minimizing the possibility of direct interactions and impacts with SSFs. However, the main competition appears to be in the fact that the same stocks are being exploited by both fleets. The three species of tropical tuna caught in the high seas by industrial fleets were also reported to be caught in coastal areas by small-scale fishers, i.e., SKJ (60% of mentions), BET and YFT (>25%). These species have been caught by SSFs over the years, but in the high SSF fishing season (December - May) in Mozambique there is overlap with the fishing seasons of industrial purse seine fleets in area (Campling, 2012; Kaplan et al., 2014; Obura et al., 2018). With respect to Mozambican tuna fisheries, the competition between industrial purse seiners and SSFs probably peaks in the high season, when fishing becomes more profitable. In the low season, when there is no industrial fishing in the region (Campling, 2012; Obura et al., 2018), competition over resources probably occurs among SSFs.

In developing countries it is common for SSFs to target the resources that offer the best abundance (easier to catch) and profit compromise to maximize income and livelihoods (McGoodwin, 2001; Tietze, 2016). Although it is seasonal, SSFs fisheries income in the high season was comparable to the income paid to staff working in the public fisheries sector (not including the high paid managerial jobs) for the period 2017-2019 (MEF et al., 2017; MEF et al., 2019). Hence, tuna fish continue to be a profitable commodity for small-scale fishers and, consequently, tuna fishing continues to attract newcomers (as perceived by the small-scale fishers interviewed), which leads to increases in the fishing effort (Gordon, 1954; Panayotou, 1982; Pitcher and Lam, 2015) and intensifies competition (Campling, 2012).

Socially, small-scale purse seine fleets provide more jobs in Mozambique (61% of total fishing-related jobs) than gillnet and handline fishing. With a total of 954 jobs generated by SSFs targeting tuna in the three regions analysed, it is estimated that Mozambique requires ~160 small-scale fishers to land a tonne of tuna. As a comparison, the Maldives requires 180 fishers, Iran 956 fishers, and the EU industrial purse seines in WIO region, only six people (Lecomte et al., 2017a; Lecomte et al., 2017b). These figures do not include the extensive value chain of small-scale fishers, with an intricate web of middlemen that in many cases distribute the fish from the villages to the main cities and neighbouring countries. Despite that small purse seine employ many fishers, interviewed operating this gear type and gillnet were met in northern area of Mozambique (region A and B) where fishers developed experience of building and operation this gear types for fishing. Also, the environmental marine system or substrate, types of fisheries resources targeted, combining with fishers handling experience of this types of gears (small purse seines and gillnet) and management systems could be the factors for using this fishing gear in northern area (McGoodwin, 2001), while in region C, the targeted species (excluding tuna in list of main target species), fishing cultural systems, surveillance and management favorable hand line fishing.

The findings of this study contribute to a better understanding of the three pillars of tuna fisheries sustainability in Mozambique, i.e., ecological, economic and social (Asche et al., 2018). In terms of ecological sustainability, the findings of this study suggest that the local catches of tropical tuna in Mozambique have been declining over the last 10 years. Although part of this decline can be attributed to piracy, which has forced some fleets out of the region, real stock declines cannot be dismissed, especially considering that small-scale fishers, who are not subject to piracy, have also noticed this decline. While the causes of the decline are not clear, as a precautionary approach, improved management measures should be considered at both local and international levels, along with improved fisheries data collection and investments in scientific research. Economically and socially, there is still room to make fishing agreements more beneficial to the Mozambican population, by ensuring that both transhipments and processing occur domestically, thereby generating more jobs, ensuring that part of the profits and revenues circulate within the country, and enforcing some accountability (POSEIDON et al., 2014; Lecomte et al., 2017b; James et al., 2018). Furthermore, the government should actively enforce the non-use of the reserved nearshore fishing grounds (<12 nm) by industrial fisheries to decrease potential future conflicts between small-scale and industrial fisheries. Moreover, the fish harvested by small-scale fishers should also be counted and incorporated into official national statistics (Kleiber, 1991; Leroy et al., 2016). Finally, economic diversification and improved the literacy rates among small-scale fishers should be promoted in order to better prepare them for future resource failures, whether it be caused by overfishing, climate change or any other factor (Fatunla, 1997; FAO, 2006; Maddox, 2007).

3.6. Conclusions

This study suggests that nominal tuna catches have been declining over time in Mozambique, regardless of whether the fish are caught by industrial or small-scale fishers. Competitive interactions among industrial fleets and SSFs over valuable commercial tuna species, such as *K. pelamis* (SKJ), *T. albacore* (YFT) and *T. obesus* (BET), have possibly been contributing to this decline given that the same stocks are being harvested in different regions of the WIO (coastal and high seas) and by all types of gear. The fact that there may be some interaction between industrial fisheries and SSFs, particularly in some regions (e.g.: villages in Inhambane and Maputo provinces), contributes to the potential consequences of declining fish stocks on less powerful actors, i.e., small-scale fishers. Thus, it is important to enforce the already existing legal separation of extraction areas between small-scale and industrial fisheries. The northern coast of Mozambique was also observed to be more directly dependent on tuna fishing, as observed by both the larger number of fishers involved in the extractive segment and of other people working along the fishing value chain. Better policies and a stronger governance that facilitates and promotes landings, transhipments, and tuna and by-catch processing in Mozambique will likely improve the social and economic outcomes of both SSFs and the industrial fishing industry in the country. It is important to avoiding the social exploitation of tuna by unfair agreements in Mozambican national waters. Future agreements should be socially and ecologically fair and supported by sound management advice on the sustainability of exploitation rates. Although preliminary, this is the first study that adopts an integrative approach to understanding the effects of having economically important stocks shared by distinct types of fisheries, especially on the more vulnerable link of the chain; local small-scales fishers.

Acknowledgments

Special thanks to UEM-ESCMC for supporting fieldwork. PFML thanks CNPq for a productivity grant (301515/2019-0). This study was partly funded by a PhD scholarship from the World-Wide Funding (WWF, Agreement #R27) to the first author to carry out his study at the University of Alicante

General Discussion and Conclusions

General Discussion

This dissertation focuses on understanding tropical tuna fisheries in Mozambique Channel in a holistic way, using a variety of data, from fisheries, such as purse seine logbook and commercial data from IEO (Spanish fleets) and IOTC respectively, to environmental and socio-economic information, including direct interviews with the local fishing community, among others. The research also used additional data from the literature, including reports, dissertations, and peer review and grey literature. The compilation of all this data allowed the investigation of several key aspects of tropical tuna fisheries in the region, from better understanding the environmental preferences and spatio-temporal effects on tropical tuna fisheries using FAD and FSC strategies to the quantification of the potential effect of climate change on the main target species - skipjack, and the investigation of the interactions between industrial and local SSF communities from a socio-ecological and socio-economic point of view. In particular, we were able to identify how preferred fishing grounds look like for the industrial purse seine fishery as well as predict future fishing grounds for skipjack tuna in the region by the middle and the end of the century for both optimistic and pessimistic climate change scenarios. Besides, our understanding of the socio-ecological and economic interactions between industrial purse seine fleets and SSF targeting bigeye, skipjack and yellowfin has been improved, as well as the socio-economic implications for local fishing communities in Mozambique.

The analysis on the environmental preferences of tropical tuna fisheries in the region show highest aggregations of tuna in the northern part of MZC, with the core fishing ground next to the west tip of Madagascar. Besides the space-time interaction, the models selected SST (and its gradient), Chl-a (and its gradient), SSH, SSS, and geostrophic currents as the oceanographic variables significantly influencing tuna catches in the MZC. The interaction of large anticyclone eddies generated in the Comorian basin with the continental shelf in the northern tip of Madagascar, where many rivers discharge, contribute to the nutrient enrichment in the region, enhancing primary productivity through all the trophic levels (José et al., 2014) and attracting tuna and other large pelagic predators. The effect of eddy circulation on turbulence, mixing and dilution of waters masses between the latitudes 10ºS and 16ºS from river discharging, deep and intermediate waters flowing northward (NADW and AAIW), and saline and warm waters from the north of the Indian Ocean towards the MZC (NIDW and RSW) (e.g.: Collins et al., 2016; Charles et al., 2020), seem to create suitable habitats for tropical tuna in the area, particularly around the west coast of Madagascar. In fact, the relationship between productivity areas and tropical tuna is well known by fishermen (Tsihobot &Rijasoa, 2015), which could partially explain the high catches observed off the west coast of Madagascar and the Mozambican coast, where high quality tuna is caught by both the industrial and SSF fleets, i.e., tuna with low contents of fats as their mainly preferred diet are crustacean copepods (Sardenne et al., 2016).

Tropical tuna species in the MZC are opportunistic predators in the apex trophic level of short food chains (e.g.: Potier et al., 2004; Tew-Kai and Marsac, 2010; Potier et al., 2014; Ternon et al., 2014; Chassot et al., 2019). Previous studies characterized tropical tuna as seasonal migratory species in the Indian Ocean, attracting tuna purse seines for fishing in the MZC between March-June (Campling, 2012; Obura et al., 2018). Life history and differences in biological characteristics of the tropical tuna species are summarized in Chassot et al. (2019), and described and discussed many other authors (e.g.: Schaefer, 2001; Graham and Dickson, 2004; Zhu et al., 2010; Eveson et al., 2015; Druon et al., 2017). For example, the maximum length in the area is ~100 cm for Skipjack, ~200 cm for Yellowfin, and ~206 cm for Bigeye, corresponding respectively to the maximum size weight of ~30 Kg, ~165 Kg and ~ 207 Kg. Reproduction maturity is fast for skipjack occurring almost about six months at the sizes of the first maturity (LF) ~40 cm and ~1.3

kg, with high batch fecundity. Yellowfin and bigeye are characterized by having a later maturity, observed after the second year (LF: ~75 cm; ~8.9 Kg), and third year (LF:102 cm; 25Kg), respectively. Tropical tuna species are multi spawners, however, the growth rates and batch fecundity are respectively fast and high for skipjack, compared to yellowfin and bigeye. These reproductive and ecological traits of tropical tuna, place skipjack as the most socio-economically important species in the region, relative to the other two species, mainly for SSF. As shown by this dissertation, the seasonality and ecological preferences of tropical tuna are closely related to the suitability of oceanographic variables in the MZC, drawing optimal habitats for reproduction, growth and feeding forage during particular times of the year (Potier et al., 2004; Tew-Kai and Marsac, 2010; Chassot et al., 2019).

Projections of climate change impact on skipjack tuna catches show potential spatial temporal shifting of core fishing grounds, from the northern area of MZC towards the south of the channel, and even temperate regions, by 2050 and 2100, both under optimistic and pessimistic scenarios. Interestingly, under the pessimistic scenario, the projections also show a relocation of skipjack along the northern MZC by the end of the century. Under the optimistic and pessimistic (2050) scenarios, tuna are projected to be redistributed to current cold and temperate waters, a result consistent with other similar studies on tuna (e.g.; Marsac, 2017; Monllor-Hurtado et al., 2017). However, Suzuki et al. (2004) and Matyas (2015) suggested that the strong warming of the northern MZC could be related to the tropical cyclone formation and storm intensification, which would promote high evaporation and contribute to increased precipitation, turbulence and mixing of water masses in the region. These, and other oceanographic processes related to the water masses and circulation in the area (Ullgren et al., 2012; Collins et al., 2016), could partially explain the projected skipjack recovery in the northern part of the MZC under the pessimistic scenario by 2100. Despite the uncertainty on the magnitude of climate change impacts in the area, it seems reasonable to recommend local and regional stakeholders to start developing mechanisms that would strengthen policies and governance in the area, guaranteeing the ecological, social and economic adaptation, resilience, and sustainability and minimize the vulnerability of fishing communities (Allison et al., 2009; Lindegren and Brander, 2018).

Tropical tuna fisheries are valuable socio-economic commodities among other fisheries resources in the MZC, and despite uncertainty associated to the fisheries statistics from SSF, it is estimated that, overall (industrial plus SSF), an annual catch of ~40 thousand tonnes are extracted, generating more than 100 million USD of income value (Chassot et al., 2019). Fishing fleets in the MZC are dominated by distant water nations (e.g.: Lecomte et al., 2017a; Augustave, 2018) i.e., mostly longliners from Asia since 1950s and purse seine from Europa since 1980s (IOTC, 2018a; Lecomte et al., 2017b), while, SSF from coastal nations have been operating since the ancient period (Miyake et al., 2004), securing employments, incomes, and food supply for the communities (Lecomte et al., 2017a). Foreign fleets access regional coastal waters for tuna through FPAs (Havice and Reed, 2012; Lecomte et al., 2017b). Regionally, tuna catches landing, transshipment, and processing take place mostly in Port Victoria (Seychelles) and Port Louis (Mauritius), contributing to the social and economic benefits in those countries (POSEIDON et al., 2014; Lecomte et al., 2017a), before shipped to EU, US, Thailand and Japanese markets and distributed through various supply chains (Lecomte et al., 2017a). Meanwhile, the present analysis from industrial purse seine catches and small-scale fishers' perceptions through interviews in Mozambique, show signs of declining trend for tuna catches in recent years (2000-2015). These negative signs could be related, among others, to competing fishing on tropical tuna schools, targeted by different fleets and techniques both inshore and in the high seas (Chassot et al., 2012; Pillai, 2012; Benkenstein, 2013). Additional stressors potentially decreasing tuna catches could be those related to increase of natural mortality, such as marine pollution, acidification, or even climate change, a component largely present in this dissertation (Gruber, 2011; Dueri et al., 2014; Popova et al., 2016).

Climate change usually impacts fishing communities negatively (Allison et al., 2009; Hobday et al., 2011), with special emphasis on SSF with strong occupation rooted on a fishing system (McGoodwin, 2001; Blythe et al., 2014) or low technological capacities that enable following fish schools to the new potential fishing habitats (Daw et al., 2009), foreseen as the consequence of suitable environmental shifting. Also, the interactions between industrial purse seine and SSF with the same resources like tropical tuna, even in separate fishing grounds (Kleiber, 1991), affect mostly SSF, who are limited to nearshore waters. In accordance with previous studies (e.g.: Allison et al., 2009; Daw et al., 2009; Badjeck et al., 2010; Hanna, 2011; Lindegren and Brander, 2018), this dissertation suggest to pay attention on building policies, governance and stakeholders synergies in the MZC that are aligned with local, regional and global sustainability goals, such as the United Nations Sustainable Goals (UN, 2015), for example: (i) conservation and sustainable use of the oceans, seas, marine resources for development; (ii) taking urgent action to fight against climate change and its impact, (iii) promote inclusive and sustainable economic growth, full and productive employment, and decent works in fisheries sectors; (iv) end hunger, ensure food security, improved nutrition, and promote sustainable fisheries, (v) achieve gender equality and empower women and girls in fisheries segments chain, and (vi) alleviate poverty of fishing communities through sustainable use of fisheries resources including other forms of diversifications activities for livelihoods mainly for SSF.

At the level of the environmental preferences of tropical tuna fisheries in MZC:

- The environmental conditions, such as sea surface temperature and its variability, productivity, sea surface height, and the interactions of spatial and temporal variables seem to significantly shape preferred fishing habitat conditions for both FAD and FSC fishing.

- The particular response and dynamics of each environmental variable on tropical tuna catches along the Mozambique Channel varies for each fishing mode. The models predicted better fishing grounds for FAD fishing between 10ºS to 18ºS, with the main core, in general, around the north-western coast of Madagascar. Predictions for FSC show higher catches, principally, in the northern part of the Mozambique Channel and close to the Mozambican coast between 10ºS to 16ºS.

- Despite the differences in the final descriptive models, Partial overlap exists between the predicted fishing grounds for both FAD and FSC in certain areas of the Mozambique Channel (e. g:. northern-west tip of Comoros Islands at the latitude <12ºS, and south-west coast of Madagascar at the cross section >42ºE/<14ºS).

- The results highlighted by this investigation describe in detail the connection between the biophysical state of the oceans and purse seine tuna fisheries in the MZC, which can ultimately contribute to the scientific advice and management of the exploited resources in the area.

At the level of the potential effects of climate change on the distribution of the main target species, skipjack, in the MZC:

- According to the model, the skipjack current distribution in the MZC will change, at different levels, under either the optimistic (RCP2.6) or pessimistic (RCP8.5) climate change scenarios. The optimistic scenario projects a shift in skipjack tuna catches towards the southern part of the MZC, (between latitudes 19ºS and 25ºS) by 2050, and a minor redistribution (or even no change) from 2050 to 2100. The worst-case scenario projects a change in potential fishing grounds towards latitudes >20ºS by 2050, and positive anomalies likely occurring at latitudes < 20ºS between 2050 and 2100. Besides, by the end of the century, a redistribution of skipjack is expected towards the temperate regions outside the MZC (latitudes >25ºS).

- Climate change is expected to impact skipjack distribution in the MZC, and ultimately access to fisheries, which may create significant socioeconomic challenges for fishing communities. Coastal states in the MZC region, as well as t-RFMOs, should develop adaptive governance and effective policies to guarantee the resilience of local, regional and international fisheries.

- he results of the projections will contribute to increase awareness about climate change among stakeholders and the need to develop more participatory strategies to mitigate it, such as adaptive co-management or inclusive MSP, where uncertainty, differences in priorities, traditional knowledge and other important elements are addressed.

At the level of the socio-ecological and economic interactions between industrial and artisanal tropical tuna fisheries in Mozambique:

- Nominal tuna catches seem to have been declining over time in Mozambique from industrial fisheries while small-scale fishers' responses were inconsistent about increasing and decreasing of tuna catch trend. Competing interactions among industrial fleets and SSFs over tropical tuna species have possibly been contributing to this decline given that the same stocks are being targeted in different regions of the WIO (coastal and high seas) and by all types of gear.

- The interaction in some fishing grounds between industrial fisheries and SSFs, particularly in some regions (e.g.: villages in Inhambane and Maputo provinces), may contribute to emphasize the decline of catches by less powerful actors, i.e., small-scale fishers. Finding mechanisms to protect small-scale fishers, such as strengthening the enforcement of the already existing legal separation of extraction areas, is desirable for an improved co-existence of different fisheries operating in the region.

- The northern coast of Mozambique was also observed to be more directly dependent on tropical tuna fishing, as observed by both the larger number of fishers involved in the extractive segment and of other people working along the fishing value chain. Better policies and a stronger governance that facilitates and promotes landings, transhipments, and tuna and by-catch processing in Mozambique will likely improve the social and economic outcomes of both SSFs and the industrial fishing industry in the country.

- Maintaining sustainable tuna exploitation rates both locally and internationally is important to guarantee medium and long-term fishing access to Mozambican fishermen. Future fishing agreements with foreign fleets should be socially and ecologically sustainable and supported by sound management advice on the exploitation rates.

- The integrative approach adopted in this study helps to understand the potential effects of sharing economically important stocks by different fisheries, especially those affecting the most vulnerable link of the chain; local small-scales fishers. These findings may contribute to raise awareness of all stakeholders, such as fishers, managers, and decision-makers, among others, to address policies and governances toward sustainable goals.

The limitations of this dissertation, along with the main results obtained, highlighted several potential lines of investigation that could benefit the scientific community and the conservation and management of the exploited species in the short, medium and long-term.

With regards the environmental preferences of tuna fisheries and species:

a) Conduct species-specific and size-specific environmental preferences analyses, with particular emphasis on juvenile yellowfin and bigeye;
b) Develop models using fisheries independent information, such as tagging data or acoustic data from echo-sounder buoys, to improve consistency of results and explore potential differences;
c) Conduct similar models using additional or alternative fisheries data, such as, including detailed small-scale fisheries data or information from other industrial fleets (e. g:. other flags of purse seiners, longliners) operating in the area;
d) Develop models that integrate other environmental variables, particularly those related to the subsurface component of the habitat (e. g:. mixed layer depth, oxygen concentration).

With regards to the assessment of climate change impacts on the fisheries operating in the region:

a) Model the distribution of skipjack under other climate change scenarios, such as the short term decadal scale climatological models available in other data provision agencies (e.g.: IPSL-CMC6 – Institute Pierre Siomon Laplace Climate Modelling Center; NOAA – GDFL National Oceanic and Atmospheric Administration – Geophysical Dynamic Fluid Laboratory);
b) Conduct species, set-type and size-specific models of potential climate change impact, with particular emphasis on juvenile yellowfin and bigeye;
c) Include, when available, other environmental variables for future predictions of tropical tuna, such as ocean acidification or salinity.

With regards the investigation of the socioecological interactions between SSF and Industrial fleets targeting tuna and tuna like species in the area:

a) Conduct tagging and/or mark and recapture studies of tuna and tuna-like species to investigate the connectivity and magnitude of interactions between fleets;
b) Conduct interviews with fishers for better understand the perceptions on climate changes impacts in local communities;
c) Establish strategies to effectively communicate scientific findings with local fishing communities and other relevant stakeholders;
d) Develop frameworks to create inclusive decision-making processes, with special emphasis on adaptations and resilience plans for local, national and regional fishing communities.

References

Afonso, N., António, E. de A., Rombe, C.M., 2017. Boletim Estatístico da Pesca e Aquacultura. Ministério do Mar, Águas Interiores e Pescas. Maputo, 64pp. http://www.mimaip.gov.mz.

Allison, E.H., Perry, A.L., Badjeck, M.C., Neil Adger, W., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., Dulvy, N.K., 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish Fish. 10, 173–196. https://doi.org/10.1111/j.1467-2979.2008.00310.x

Aral, M.M., Guan, J., 2016. Global sea surface temperature and sea level rise estimation with optimal historical time lag data. Water (Switzerland) 8. https://doi.org/10.3390/w8110519

Aral, M.M., Guan, J., Chang, B., 2012. Dynamic system model to predict global sea-level rise and temperature change. J. Hydrol. Eng. 17, 237–242. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000447

Arrizabalaga, H., Dufour, F., Kell, L., Merino, G., Ibaibarriaga, L., Chust, G., Irigoien, X., Santiago, J., Murua, H., Fraile, I., Chifflet, M., Goikoetxea, N., Sagarminaga, Y., Aumont, O., Bopp, L., Herrera, M., Marc Fromentin, J., Bonhomeau, S., 2015. Global habitat preferences of commercially valuable tuna. Deep. Res. Part II 113, 102–112. https://doi.org/10.1016/j.dsr2.2014.07.001

Arthur, R., Heyworth, S., Pearce, J., Sharkey, W., 2019. The cost of harmful fishing subsidies, IIED Working Paper. London, 1- 32. http://pubs.iied.org/16654IIED.

Asche, F., Garlock, T.M., Anderson, J.L., Bush, S.R., Smith, M.D., Anderson, C.M., Chu, J., Garrett, K.A., Lem, A., Lorenzen, K., Oglend, A., Tveteras, S., Vannuccini, S., 2018. Three pillars of sustainability in fisheries. Proc. Natl. Acad. Sci. U. S. A. 115, 11221–11225. https://doi.org/10.1073/pnas.1807677115

Assis, J., Tyberghein, L., Bosch, S., Verbruggen, H., Serrão, E.A., De Clerck, O., 2017. Bio-ORACLE_Extending marine data layers for bioclimatic modelling.pdf. Glob. Ecol. Biogeogr. 1–8. https://doi.org/DOI: 10.1111/geb.12693

Augustave, L.C., 2018. The European Union ’ s Fisheries Agreements with third countries:The european unions’ fisheries agreements with third countries. Master Thesis, Faculty of Biosciences, Fisheries and Economics; Norwigian College of Fisheries Sciences, University of Tromsø, Norway, 45pp. https://uit.no/enhet/nfh, Tromso.

Babbie, E., 2012. The Pratice of Scial Research, 13th ed. International Edition.

Badjeck, M.C., Allison, E.H., Halls, A.S., Dulvy, N.K., 2010. Impacts of climate variability and change on fishery-based livelihoods. Mar. Policy 34, 375–383. https://doi.org/10.1016/j.marpol.2009.08.007

Barange, M., Merino, G., Blanchard, J.L., Scholtens, J., Harle, J., Allison, E.H., Allen, J.I., Holt, J., Jennings, S., 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat. Clim. Chang. 4, 211–216. https://doi.org/10.1038/nclimate2119

Barclay, K., Cartwright, I., 2007. Governance of tuna industries: The key to economic viability and sustainability in the Western and Central Pacific Ocean. Mar. Policy 31, 348–358. https://doi.org/10.1016/j.marpol.2006.09.007

Barkley, R., Nell, W., Gooding, R., 1978. Skipjack tuna, Katsuwonus pelamis, habitat based on temperature and oxigen requirements. Fish. Bull. 76, 653–662.

Béhagle, N., Du Buisson, L., Josse, E., Lebourges-Dhaussy, A., Roudaut, G., Ménard, F., 2014. Mesoscale features and micronekton in the Mozambique Channel: An acoustic approach. Deep. Res. Part II Top. Stud. Oceanogr. 100, 164–173. https://doi.org/10.1016/j.dsr2.2013.10.024

Benkenstein, A., 2013. Small-Scale Fisheries in a Modernising Economy : Opportunities and Challenges in Mozambique. Research Report 13, South Africa, 55pp. https://saiia.org.za.

Bergeron, L., 2014. The forgotten chokepoint: The Mozambique Channel’s rich past and bright but insecure future. Risk Intelligence, Strategic Insights Nº 54, Vedbaek, Denmark, 10pp. https://riskintelligence.eu/.

Bivand, R.S., Pebesma, E., Gómez-Rubio, V., 2015. Applied Spatial Data Analysis with R, Second. ed, Spatial Demography. Springer Science, New York -USA. https://doi.org/10.1007/bf03354901

Bjørnstad, O.N., Falck, W., Barbara, S., State, P., 2001. Nonparametric spatial covariance functions: Estimation and testing. Environ. Ecol. Stat. 8, 53–70. https://doi.org/10.1023/A:1009601932481

Blythe, J.L., 2015. Resilience and social thresholds in small-scale fishing communities. Sustain. Sci. 10, 157–165. https://doi.org/10.1007/s11625-014-0253-9

Brander, K., 2008. Tackling the old familiar problems of pollution, habitat alteration and overfishing will help with adapting to climate change. Mar. Pollut. Bull. 56, 1957–1958. https://doi.org/10.1016/j.marpolbul.2008.08.024

Campling, L., 2012. The Tuna “Commodity Frontier”: Business Strategies and Environment in the Industrial Tuna Fisheries of the Western Indian Ocean. J. Agrar. Chang. 12, 252–278. https://doi.org/10.1111/j.1471-0366.2011.00354.x

Cardinale, M., Linder, M., Bartolino, V., Maiorano, L., Casini, M., 2009. Conservation value of historical data:

Reconstructing stock dynamics of turbot during the last century in the Kattegat-Skagerrak. Mar. Ecol. Prog. Ser. 386, 197–206. https://doi.org/10.3354/meps08076

Chacate, O.E., Mutombe, R., 2018. Mozambique National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2018. Indian Ocean Tuna Commission. Maputo, Mozambique, 28pp. https://www.iotc.org.

Chacate, O.E., Mutombene, R., 2019. Mozambique National Report to the Scientific Committee of the Indian Ocean Tuna Commission, 2019. IOTC. Indian Ocean Tuna Commission. Maputo, Mozambique, 25 pp. https://www.iotc.org.

Charles, C., Pelleter, E., Révillon, S., Nonnotte, P., Jorry, S.J., Kluska, J.M., 2020. Intermediate and deep ocean current circulation in the Mozambique Channel: New insights from ferromanganese crust Nd isotopes. Mar. Geol. 430. https://doi.org/10.1016/j.margeo.2020.106356

Chassot, E., Bodin, N., Sardenne, F., Obura, D., 2019. The key role of the Northern Mozambique Channel for Indian Ocean tropical tuna fisheries. Rev. Fish Biol. Fish. 1–27. https://doi.org/10.1007/s11160-019-09569-9

Chassot, E., Guillotreau, P., Kaplan, D., Vallée, T., 2012. The tuna fishery and piracy. Piracy Comp. Perspect. Probl. Strateg. laws.

Cheung, W.W.L., Watson, R., Pauly, D., 2013. Signature of ocean warming in global fisheries catch. Nat. Macmillan Publ. Limited. 497, 365–368. https://doi.org/10.1038/nature12156

Collins, C., Hermes, J., Roman, R., Resason, C., 2016. First dedicated hydrographic Survey of the Comoros Basin. J. od Geophys. Res. Ocean. 1–15. https://doi.org/10.1002/2015JC011418

Collins, M., Knutti, R., Arblaster, J., Dufrense, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowsk, W., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A., Wehner, M., 2013. Long-Term Climate Change_Projections_Comiyments and Irreversibility. In: Climate Change 2013; The Physical Science Basisi, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernamental Panel on Climate Change [Stocker, T. F., D. Cambridge University Press,Cambridge, United Kingdom and New Yor, Ny, USA.

Cortés-Avizanda, A., Almaraz, P., Carrete, M., Sánchez-Zapata, J.A., Delgado, A., Hiraldo, F., Donázar, J.A., 2011. Spatial heterogeneity in resource distribution promotes facultative sociality in two trans-saharan migratory birds. PLoS One 6, 1–11. https://doi.org/10.1371/journal.pone.0021016

Damasio, L.D.M.A., Lopes, P.F.M., Pennino, M.G., Carvalho, A.R., Sumaila, U.R., 2016. Size matters: Fishing less and yielding more in smaller-scale fisheries. ICES J. Mar. Sci. 73, 1494–1502. https://doi.org/10.1093/icesjms/fsw016

Davies, S., Markides, M., 2019. The Status and Future of Sustainable Fisheries Partnership Agreements in the South West Indian Ocean. Stop Illegal Fishing, Belgium, 44pp. https://www.wwf.eu.

Davies, T.K., Mees, C.C., Milner-Gulland, E.., 2014. Modelling the Spatial Behaviour of a Tropical Tuna Purse Seine Fleet. PLoS One 9, 1–18. https://doi.org/10.1371/journal.pone.0114037

Daw, T., Adger, W.N., Brown, K., 2009. Climate Change and Capture Fisheries: potential impacts, adatpation and mitigation, in: K, C., C, D.Y., D, S., Bahri T (Eds.), Climate Chate Implications for Fisheries: Overview of Current Scientific Knowledge. FAO Fisheries and Aquaculture Technical Paper. Nº.530. Rome, FAO., pp. 107–150.

De Melo Alves Damasio, L., Lopes, P.F.M., Guariento, R.D., Carvalho, A.R., 2015. Matching Fishers' knowledge and landing data to overcome data missing in small-scale fisheries. PLoS One 10, 1–13. https://doi.org/10.1371/journal.pone.0133122

de Ruijter, W.P.M., Brummer, G.J.A., Drijfhout, S.S., Lutjeharms, J.R.E., Peeters, F., Ridderinkhof, H., van Aken, H., van Leeuwen, P.J., 2006. Observations of the inter-ocean exchange around South Africa. Eos (Washington. DC). 87, 100–102. https://doi.org/10.1029/2006eo090002

Delignette-Muller, M., Dutang, C., 2015. Fitdistrplus: An R Package for Fitting Distributions. J. Stat. Software, 64, 1–34.

Dell, J., Wilcox, C., Hobday, A.J., 2011. Estimation of yellowfin tuna (Thunnus albacares) habitat in waters adjacent to Australia's East Coast: Making the most of commercial catch data. Fish. Oceanogr. 20, 383–396. https://doi.org/10.1111/j.1365-2419.2011.00591.x

Dey, M.M., Gosh, K., Valmonte-Santos, R., Rosegrant, M.W., Chen, O.L., 2016. Economic impact of climate change and climate change adaptation strategies for fisheries sector in Fiji. Mar. Policy 67, 164–170. https://doi.org/10.1016/j.marpol.2015.12.023

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., Mcclean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. Ecography (Cop.). 36, 027–046. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Druon, J., Chassot, E., Murua, H., 2017. Skipjack Tuna Availability for Purse Seine Fisheries Is Driven by Suitable Feeding Habitat Dynamics in the Atlantic and Indian Oceans. Front. Mar. Sci. 4, 1–17. https://doi.org/10.3389/fmars.2017.00315

Dueri, S., Bopp, L., Maury, O., 2014. Projecting the impacts of climate change on skipjack tuna abundance and spatial distribution. Glob. Chang. Biol. 20, 742–753. https://doi.org/10.1111/gcb.12460

Dueri, S., Faugeras, B., Maury, O., 2012. Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E : Part 1 . Model formulation Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E : Part 1 . Model formulation. Ecol. Modell. 245, 41–54. https://doi.org/10.1016/j.ecolmodel.2012.02.007

Duffy, J.E., Lefcheck, J.S., Stuart-smith, R.D., Navarrete, S.A., Edgar, G.J., 2016. Biodiversity enhances reef fish biomass and resistance to climate change. PNAS 113, 6230–6235. https://doi.org/10.1073/pnas.1524465113

Dulvy, N., Reynolds, J., Graham, P., Pinnegar, J., Philips, J.S., Allison, E., Badjeck, M.-C., 2011. Fisheries management and governance challenges in a climate change, in: Davis, J. (Ed.), The Economics of Adapting Fisheries to Climate Change. pp. 33–89. https://doi.org/doi.org/10.1787/9789264090415-en

EC, 2012. Protocol setting out the fishing opportunities and the financial contribution provided for by the Fisheries Partnership Agreement between the European Community and the Republic of Mozambique. Off. J. Eur. Union 46, 4–29.

EC, 2007. on the conclusion of an Agreement in the form of an Exchange of Letters on the provisional application of the Fisheries Partnership Agreement between the European Community and the Republic of Mozambique. Off. J. Eur. Union 331, 31–54.

EC, 2003. Proposal for a Council Regulation on the conclusion of the Fisheries Agreement between the European Community and the Republic of Mozambique. COM/2003/0419 Final - CNS 2003/0154 0154, 1–44.

EC, 1987. Protocol establishing the fishing rights and contributions provided for in the Agreement between the European Economic Community and the Government of the People's Republic of Mozambique on fisheries relations. Off. J. Eur. Communities 98, 10–24.

Erauskin-Extramiana, M., Arrizabalaga, H., Hobday, A.J., Cabré, A., Ibaibarriaga, L., Arregui, I., Murua, H., Chust, G., 2019. Large-scale distribution of tuna species in a warming ocean. Glob. Chang. Biol. 25, 2043–2060. https://doi.org/10.1111/gcb.14630

FAO, 2006a. Review of the state of world marine capture fisheries management : Indian Ocean. FAO Fisheries Technical Paper, Rome, Italy.

FAO, 2006b. Promoting literacy to improve livelihoods in fishing commuities - Policies linking education to fisheries management. New Direction in Fisjeries, A Series of Policy Briefs on Development Issues, Nº 05. Rome. 12pp. http://www.sflp.org/briefs/eng/policybriefs.html.

Fatunla, G.T., 1997. Socio-Economic Issues in the Education of Children of Migrant Fishermen in Nigeria. J. Sustain. Agric. 9, 31–61. https://doi.org/10.1300/J064v09n01_05

Fonteneau, A., Chassot, E., Bodin, N., 2013. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. Aquat. Living Resour. 26, 37–48. https://doi.org/10.1051/alr/2013046

Fonteneau, A., Hallier, J.P., 2015. Fifty years of dart tag recoveries for tropical tuna: A global comparison of results for the western Pacific, eastern Pacific, Atlantic, and Indian Oceans. Fish. Res. 163, 7–22. https://doi.org/10.1016/j.fishres.2014.03.022

Fraile, I., Murua, H., Goni, N., Caballero, A., 2010. Effects of environmental factors on catch rates of FAD-associated yellowfin (Thunnus albacares) and skipjack (Katsuwonus pelamis) tunas in the western Indian Ocean. IOTC Proc. IOTC-2010-WPTT-46 22.

Giannoulaki, M., Iglesias, M., Tugores, M.P., Bonanno, A., Patti, B., De Felice, A., Leonori, I., Bigot, J.L., Tičina, V., Pyrounaki, M.M., Tsagarakis, K., Machias, A., Somarakis, S., Schismenou, E., Quinci, E., Basilone, G., Cuttitta, A., Campanella, F., Miquel, J., Oñate, D., Roos, D., Valavanis, V., 2013. Characterizing the potential habitat of European anchovy Engraulis encrasicolus in the Mediterranean Sea, at different life stages. Fish. Oceanogr. 22, 69–89. https://doi.org/10.1111/fog.12005

Gordon, H.. S., 1954. The Economic Theory of a Common-Property Resource : The Fishery. J. Polit. Econ. http//www.jstor.org/stable/1825571 62, 124–142.

Grafton, R.Q., 2010. Adaptation to climate change in marine capture fisheries. Mar. Policy 34, 606–615. https://doi.org/10.1016/j.marpol.2009.11.011

Graham, J.B., Dickson, K.A., 2004. Tuna comparative physiology. J. Exp. Biol. 207, 4015–4024. https://doi.org/10.1242/jeb.01267

Grolemund, G., Wickham, H., 2011. Dates and times made easy with lubridate. J. Stat. Softw. 40, 1–25. https://doi.org/10.18637/jss.v040.i03

Gruber, N., 2011. Warming up, turning sour, losing breath: Ocean biogeochemistry under global change. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 369, 1980–1996. https://doi.org/10.1098/rsta.2011.0003

Grynberg, R., 2003. WTO fisheries subsidies negotiations : implications for fisheries access arrangements and sustainable management. Mar. Policy 27, 499–511. https://doi.org/10.1016/S0308-597X(03)00064-2

Hampton, J., 1991. A review of tuna fishery-interaction issues in the western ani central Pacific Ocean, in: Interactions of Tuna Fisheries. R.S. Shomura, J. Majkowski, R.F. Harman (Eds.). FAO Fisheries Technical Paper, 336/1, Rome, 1994, pp. 138–157.

Hanna, S., 2011. Economic and policy issues related to the impact of climate change on fisheries, in: Davis, J. (Ed.), The Economics of Adapting Fisheries to Climate Change. pp. 91–116. https://doi.org/10.1787/9789264090415-en

Hastenrath, S., 2015. Tropical Meteorology and Climate: Tropical Climates, in: Encyclopedia of Atmospheric Sciences: Second Edition. https://doi.org/10.1016/B978-0-12-382225-3.00416-3

Havice, E., Reed, K., 2012. Fishing for Development? Tuna Resource Access and Industrial Change in Papua New Guinea. J. Agrar. Chang. 12, 413–435. https://doi.org/10.1111/j.1471-0366.2011.00351.x

Hobday, A.J., Pecl, G.T., 2014. Identification of global marine hotspots: Sentinels for change and vanguards for adaptation action. Rev. Fish Biol. Fish. 24, 415–425. https://doi.org/10.1007/s11160-013-9326-6

Hoguane, A.M., 2007. Perfil Diagnóstico da Zona Costeira de Moçambique. Rev. Gestão Costeira Integr. 7, 69–82. https://doi.org/10.5894/rgci11

Houssard, P., Lorrain, A., Tremblay-Boyer, L., Allain, V., Graham, B.S., Menkes, C.E., Pethybridge, H., Couturier, L.I.E., Point, D., Leroy, B., Receveur, A., Hunt, B.P.V., Vourey, E., Bonnet, S., Rodier, M., Raimbault, P., Feunteun, E., Kuhnert, P.M., Munaron, J.M., Lebreton, B., Otake, T., Letourneur, Y., 2017. Trophic position increases with thermocline depth in yellowfin and bigeye tuna across the Western and Central Pacific Ocean. Prog. Oceanogr. 154, 49–63. https://doi.org/10.1016/j.pocean.2017.04.008

Huggett, J.A., 2014. Mesoscale distribution and community composition of zooplankton in the Mozambique Channel. Deep. Res. Part II 100, 119–135. https://doi.org/10.1016/j.dsr2.2013.10.021

Huntington, H.P., 2000. Using traditional ecological knowledge in science: Methods and applications. Ecol. Appl. 10, 1270–1274. https://doi.org/10.1890/1051-0761(2000)010[1270:UTEKIS]2.0.CO;2

IOTC, 2020. Nominal catch by species and gear, by vessel flag reporting country [www document]. Iotc-2019-datasets-ncdb. [WWW Document]. IOTC-2019-DATASETS-NCDB. URL https://www.iotc.org/data/datasets/latest/NC

IOTC, 2018. Status summary for species of tuna and tuna-like species under the iotc mandate, as well as other species impacted by iotc fisheries. Victoria Mahé, Seychelles, 8pp. https://www.iotc.org.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]., IPCC. Geneva, Switzerland,151 pp. http://www.ipcc.ch.

Jame, D., Hornik, K., 2013. Chronological Objects which can Handle Dates and Times [WWW Document]. https://CRAN.R-project.org/package=chron.

James, G., Witten, D., Hastie, T., Tibshirani, R., 2014. An Introduction to Statistical Learning with Application in R, Springer Texts in Statistics. https://doi.org/10.1016/j.peva.2007.06.006

James, P.A.S., Tidd, A., Paka, L., 2018. The impact of industrial tuna fishing on small-scale fishers and economies in the Pacific. Mar. Policy 1–10. https://doi.org/10.1016/j.marpol.2018.03.021

Jones, A.R., Hosegood, P., Wynn, R.B., De Boer, M.N., Butler-Cowdry, S., Embling, C.B., 2014. Fine-scale hydrodynamics influence the spatio-temporal distribution of harbour porpoises at a coastal hotspot. Prog. Oceanogr. 128, 30–48. https://doi.org/10.1016/j.pocean.2014.08.002

Kalikoski, D.C., Quevedo Neto, P., Almudi, T., 2010. Building adaptive capacity to climate variability: The case of artisanal fisheries in the estuary of the Patos Lagoon, Brazil. Mar. Policy 34, 742–751. https://doi.org/10.1016/j.marpol.2010.02.003

Kaplan, D.M., Chassot, E., Amande, J.M., Dueri, S., Dagorn, L., Fonteneau, A., Amandé, J.M., Dueri, S., Demarcq, H., Dagorn, L., Fonteneau, A., Amande, J.M., Dueri, S., Dagorn, L., Fonteneau, A., 2014. Spatial management of Indian Ocean tropical tuna fisheries : Potential and Perspectives. ICES J. Mar. Sci. 71, 1728–1749.

Kleiber, P., 1991. Types of tuna fishery interaction in the pacific ocean and methods of assessing interaction, in: Interactions of Tuna Fisheries. R.S. Shomura, J. Majkowski, R.F. Harman (Eds.). FAO Fisheries Technical Paper 336/1, Rome, 1994, pp. 61–63.

Lali, C., Parsons, T., 2006. Biological Oceanography: An Introduction, 2nd ed. Second Edition, University of British Columbia, Vancouver, Canada, ISBN 0-7506-3384-0, 1 - 337.

Lan, K.W., Shimada, T., Lee, M.A., Su, N.J., Chang, Y., 2017. Using remote-sensing environmental and fishery data to map potential yellowfin tuna habitats in the Tropical Pacific Ocean. Remote Sens. 9, 1–14. https://doi.org/10.3390/rs9050444

Lecomte, M., Rochette, J., Lapeyre, R., 2017a. Sustainable management of tuna fisheries: a synthesis report, Développment Durable & Relations Internationales, https://www.iddri.org. Paris, France. pp. 1-48.

Lecomte, M., Rochette, J., Laurans, Y., Lapeyre, R., 2017b. Indian Ocean tuna fisheries: between development opportunities and sustainability issues, Développment Durable & Relations Internationales, https://www.iddri.org. Paris, France. 1-96 pp.

Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell, J.D., Sibert, J., 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change, in: Bell, J D, Johnson, J.E., Hobday, A.J. (Eds.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.

Secretariat of the Pacific Community, Noumea, New Caledonia., pp. 433–492.

Lehodey, P., Senina, I., Calmettes, B., Hampton, J., Nicol, S., 2013. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Clim. Change 119, 95–109. https://doi.org/10.1007/s10584-012-0595-1

Lehodey, P., Senina, I., Nicol, S., Hampton, J., 2015. Modelling the impact of climate change on south pacific albacore tuna. Deep. Res. Part II Top. Stud. Oceanogr. 113, 246–259. https://doi.org/10.1016/j.dsr2.2014.10.028

Lehodey, P., Senina, I., Sibert, J., Bopp, L., Calmettes, B., Hampton, J., Murtugudde, R., 2010. Preliminary forecasts of Pacific bigeye tuna population trends under the A2 IPCC scenario. Prog. Oceanogr. 86, 302–315. https://doi.org/10.1016/j.pocean.2010.04.021

Leroy, B., Peatman, T., Usu, T., Caillot, S., Moore, B., Williams, A., Nicol, S., 2016. Interactions between artisanal and industrial tuna fisheries: Insights from a decade of tagging experiments. Mar. Policy 65, 11–19. https://doi.org/10.1016/j.marpol.2015.12.001

Liaw, A., Matthew, W., 2002. Classification and Regression by randomForest. R News 2, 18–22.

Lindegren, M., Brander, K., 2018. Adapting Fisheries and Their Management To Climate Change: A Review of Concepts, Tools, Frameworks, and Current Progress Toward Implementation. Rev. Fish. Sci. Aquac. 26, 400–415. https://doi.org/10.1080/23308249.2018.1445980

Lopez, J., Alvarez-Berastegui, D., Soto, M., Murua, H., 2020. Using fisheries data to model the oceanic habitats of juvenile silky shark (Carcharhinus falciformis) in the tropical eastern Atlantic Ocean. Biodivers. Conserv. 29, 2377–2397. https://doi.org/10.1007/s10531-020-01979-7

Lopez, J., Moreno, G., Lennert-Cody, C., Maunder, M., Sancristobal, I., Cabalerro, A., Dagorn, L., 2017. Environmental preferences of tuna and non-tuna species associated with drifting fish aggregating devices (DFADs) in the Atlantic Ocean, ascertained through fishers' echo-sounder buoys. Deep Sea Res. Part II 140, 127–138. https://doi.org/10.1016/j.dsr2.2017.02.007

Lopez, J., Moreno, G., Sancristobal, I., Murua, J., 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fish. Res. 155, 127–137. https://doi.org/10.1016/j.fishres.2014.02.033

Lopez, J., Scott, G.P., 2014. The use of FADs in tuna fisheries. Eur. Union. Dir. Gen. Intern. Policies. 164, 1–16.

Loukos, H., Monfray, P., Bopp, L., Lehodey, P., 2003. Potential changes in skipjack tuna (Katsuwonus pelamis) habitat from a global warming scenario : modelling approach and preliminary results. Fish. Oceanogr. 12, 474–482.

Lutjeharms, J.O.R.E.L., Town, C., 2006. The Coastal Oceans of South-Eastern Africa. Africa (Lond). 14, 783–834.

Maddox, B., 2007. Literacy in Fishing Communities. FAO, Sustain. Fish. Livelihoods Program. 17.

Mailu, S., Ngila, M., Wamukota, A., Officer, F., Directorate, F., Box, P.O., 2015. Tuna Fisheries within the West Indian Ocean : Is there a role for COMESA ?, SSRN. https://doi.org/http://dx.doi.org/10.2139/ssrn.2597864

Mann, K.H., Lazier, J.R.N., 2006. Dynamics of Marine Ecosystems: Biological--Physical Interactions in the Oceans., Third Edit. ed, Blackwell Publishing. Victoria, Australia, ISBN-13: 978-1-4051-1118-8. https://doi.org/10.2307/2260704

Marsac, F., 2017. The Seychelles Tuna Fishery and Climate Change, in: Philips, B., Pérez-Ramírez, M. (Eds.), Climate Change Impacts on Fisheries and Aquaculture. Wiley Blackwell, pp. 523–568. https://doi.org/10.1002/9781119154051.ch16

Matsumoto, W.M., Skillman, R.A., Dizon, A.E., 1984. Synopsis of biological data on Skipjack tuna, Katsuwonus pelamis. FAO Fisheries, NOAA, Department of Cmmerce, US, 1 -99.

Matyas, C.J., 2015. Tropical cyclone formation and motion in the Mozambique Channel. Int. J. Climatol. 35, 375–390. https://doi.org/10.1002/joc.3985

Maury, O., Gascuel, D., Marsac, F., Fonteneau, A., Rosa, A. De, 2001. Hierarchical interpretation of nonlinear relationships linking yellowfin tuna (Thunnus albacares) distribution to the environment in the Atlantic Ocean. Can. J. Fish. Aquat. Sci. 469, 458–469. https://doi.org/10.1139/cjfas-58-3-458

Mcclanahan, T.R., Maina, J.M., Muthiga, N.A., 2011. Associations between climate stress and coral reef diversity in the western Indian Ocean. Glob. Chang. Biol. 17, 2023–2032. https://doi.org/10.1111/j.1365-2486.2011.02395.x

McGoodwin, J.R., 2001. Understanding the cultures of fishing communities: a key to fisheries management and food security. FAO Fish. Tech. Pap. https://doi.org/ISSN 0429-9345

MEF, MTSS, MMAIP., 2019. Cocernente ao reajuste dos salários minimos para os trabalhadores que desenvolvem actividades integradas no sector 2 -Pesacas. Bol. da República, Imprensa Nac. Moçambique, Diploma Minist. no 42/2017. Maputo, Moçambique. 983–986. https://doi.org/https://www.inm.gov.mz/

MEF, MTSS, MMAIP., 2017. Reajusta salários mínimos para os trabalhadores que desenvolvem actividades no sector 2 -Pescas. Bol. da República, Imprensa Nac. Moçambique, Diploma Minist. nº 32/2017, Maputo, Moçambique 422–524. https://doi.org/https://www.inm.gov.mz

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109, 213–241. https://doi.org/10.1007/s10584-011-0156-z

Mendiate, R.E.J., 2016. Exportation of Processed Fishery Products from Mozambique: Determinants and Technical Compliance Process. PhD Thesis, Nagoya University, Japan, 231pp. https://www.gsid.nagoya-u.ac.jp.

Miller, C.B., Wheeler, P.A., 2012. Biological Oceanography. Second Edition, Wiley-Blacwell Publishing, Oregon State Universit, Orego, USA,ISBN 978-1-4443-3302-2, 1 - 925.

Ministers-Council, 2017. Regulamento de Concessão de Direitos de Pesca e de Licenciamento da Pesca. Decreto n.º 74/2017, Lei 22/2013, de 1 de Novembro - Lei das Pescas, Boletim da República, I SERIE -203, Mozambique.

Monllor-Hurtado, A., Pennino, M.G., Sanchez-Lizaso, J.L., 2017. Shift in tuna catches due to ocean warming. PLoS One 12, 1–10. https://doi.org/10.1371/journal.pone.0178196

Moreno, G., Herrera, M., Morón, J., 2016a. To FAD or not to FAD: A challenge to the marine stewardship council and its conformity assessment bodies on the use of units of assessment and units of certification for industrial purse seine tuna fisheries. Mar. Policy 73, 100–107. https://doi.org/10.1016/j.marpol.2016.08.001

Moreno, G., Herrera, M., Morón, J., 2016b. To FAD or not to FAD: A challenge to the marine stewardship council and its conformity assessment bodies on the use of units of assessment and units of certification for industrial purse seine tuna fisheries. Mar. Policy 73, 100–107. https://doi.org/10.1016/j.marpol.2016.08.001

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. https://doi.org/10.1038/nature08823

Mugo, R., Saitoh, S.I., Nihira, A., Kuroyama, T., 2010. Habitat characteristics of skipjack tuna (Katsuwonus pelamis) in the western North Pacific: a remote sensing perspective. Fish. Oceanogr. 19, 382–396. https://doi.org/10.1111/j.1365-2419.2010.00552.x

Mukesh, Rohit, P., Varghese, S.P., Pandey, S., Ramalingam, L., 2019. Status of Indian tropical tuna fisheries in 2018, IOTC-2019-WPTT21-15_Review. https://iotc.org.

Mutombene, R., Sulemane, N.B., Salença, A., Jamal, G., Mauricio, E., Quibuana, T., Tagir QUIBUANA, I.C., Chacate, O., 2017. General characterization of artisanal purse seine and handline fisheries of northern coast of Mozambique and their impact on tuna and tuna like species. IOTC. Indian Ocean Tuna Commission. https://iotc.org. Maputo, Mozambique.

Nagel, P., Gray, T., 2012. Ocean & Coastal Management Is the EU ' s Fisheries Partnership Agreement (FPA) with Mauritania a genuine partnership or exploitation by the EU ? Ocean Coast. Manag. 56, 26–34. https://doi.org/10.1016/j.ocecoaman.2011.11.002

Norberg, A., Abrego, N., Blanchet, F.G., Adler, F.R., Anderson, B.J., Anttila, J., Araújo, M.B., Dallas, T., Dunson, D., Elith, J., Foster, S.D., Fox, R., Franklin, J., Godsoe, W., Guisan, A., O'Hara, B., Hill, N.A., Holt, R.D., Hui, F.K.C., Husby, M., Kålås, J.A., Lehikoinen, A., Luoto, M., Mod, H.K., Newell, G., Renner, I., Roslin, T., Soininen, J., Thuiller, W., Vanhatalo, J., Warton, D., White, M., Zimmermann, N.E., Gravel, D., Ovaskainen, O., 2019. A comprehensive evaluation of predictive performance of 33 species distribution models at species and community levels. Ecol. Monogr. 89, 1–24. https://doi.org/10.1002/ecm.1370

O'Neill, B.C., Tebaldi, C., Vuuren, D.P. van, Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9, 3461–3482. https://doi.org/doi:10.5194/gmd-9-3461-2016

Obura, D.O., Bandeira, S.O., Bodin, N., Burgener, V., Braulik, G., Chassot, E., Gullström, M., Kochzius, M., Nicoll, M., Osuka, K., Ralison, H.O., Richmond, M., Samoilys, M.A., Scheren, P., Ternon, J.-F., 2018. The Northern Mozambique Channel. World Seas an Environ. Eval. 75–99. https://doi.org/10.1016/b978-0-08-100853-9.00003-8

Orúe, B., Lopez, J., Pennino, M.G., Moreno, G., Santiago, J., Murua, H., 2020a. Comparing the distribution of tropical tuna associated with drifting fish aggregating devices (DFADs) resulting from catch dependent and independent data. Deep Sea Res. Part II Top. Stud. Oceanogr. 175, 1–6. https://doi.org/https://doi.org/10.1016/j.dsr2.2020.104747

Orúe, B., Pennino, M.G., Lopez, J., Moreno, G., Santiago, J., Ramos, L., Murua, H., 2020b. Seasonal Distribution of Tuna and Non-tuna Species Associated With Drifting Fish Aggregating Devices (DFADs) in the Western Indian Ocean Using Fishery-Independent Data. Front. Mar. Sci. 7, 1–17. https://doi.org/10.3389/fmars.2020.00441

Otterlei, L.K., 2011. The European Union Fisheries Partnership Agreements - A governability assessment of the case of the Republic of Mozambique. Master Thesis, Norwigian College of Fisheries Sciences, University of Tromsø, Norway, 119pp. https://uit.no/enhet/nfh.

Panayotou, T., 1982. Management concepts for small-scale fisheries. Economic and social aspects., FAO. Fisheries Technical Paper. http://www.fao.org. Rome, Italy.

Parks, W.W., 1991. A review of Indian Ocean fisheries for skipjack tuna, Katsuwonus pelamis, and yellowfin tuna, Thunnus albacares. Mar. Fish. Rev. 53, 1–9.

Pauly, D., 1997. Small-Scale Fisheries in the Tropics: Marginality, Marginalization, and Some Implications for Fisheries Management. In:E.K. Pikitch, D.D.Huppert and M.P.Sissenwine (eds), in: Global Trends: Fisheries Management. American Society Fishries Symposium 20, Bethesda, Marland, pp. 40–49.

Pennino, M.G., Brodie, S., Frainer, A., Lopes, P.F.M., Lopez, J., Ortega-Cisneros, K., Selim, S.A., Vaidianu, N.M., 2021. The missing layers: integrating sociocultural values into Marine Spatial Planning. Front. Mar. Sci. 8, 848. https://doi.org/10.3389/fmars.2021.633198

Perry, I., Ommer, R., Barange, M., Werner, F., 2010. The challenge of adapting marine social–ecological systems to the additional stress of climate change.pdf. Curr. Opin. Environ. Sustain. 2, 356–363. https://doi.org/10.1016/j.cosust.2010.10.004

Pierce, D., 2017. ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files [WWW Document]. https://CRAN.R-project.org/package=ncdf4.

Pillai, P.P., 2012. Impact of piracy on fisheries in the lndian Ocean. Fish. Chimes 32, 25–28.

Pitcher, T.J., Lam, M.E., 2015. Fish commoditization and the historical origins of catching fish for profit. Marit. Stud. a SpringOpen J. 14, 1–19. https://doi.org/10.1186/s40152-014-0014-5

Popova, E., Yool, A., Byfield, V., Cochrane, K., Coward, A.C., Salim, S.S., Gasalla, M.A., Henson, S.A., Hobday, A.J., Pecl, G.T., Sauer, W.H., Roberts, M.J., 2016. From global to regional and back again: Common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. Glob. Chang. Biol. 22, 2038–2053. https://doi.org/10.1111/gcb.13247

POSEIDON, MRAG, NFDS, COFREPECHE, 2014. Review of tuna fisheries in the Western Idian Ocean (framework contract MARE/2011/01- Lot3, specific contract 7). https://dokumen.tips/documents/v1. Brussel, Belgian, pp. 1-165.

Potier, M., Bach, P., Ménard, F., Marsac, F., 2014. Influence of mesoscale features on micronekton and large pelagic fish communities in the Mozambique Channel. Deep Sea Res. Part II 100, 184–199.

QGIS Development Team, 2018. QGIS 3.4 Geographic Information System. Open Source Geospatial Found. Proj. https://doi.org/http://www.qgis.org/

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria 0, 201. https://doi.org/10.1108/eb003648

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science (80-.). 315, 368–370. https://doi.org/10.1126/science.1135456

Rajapaksha, J.K., Samarakoon, L., Gunathilaka, A.A.J.K., 2013. Environmental Preferences of Yellowfin Tuna in the North East Indian Ocean: An Application of Satellite Data to Longline Catches Improvement of Tuna fishing ground forecast system of NARA View project Engineering Geological, Hydrogeological, and Geotechni. Int. J. Fish. Aqauatic Sci. 2, 72–80.

Ramírez, F., Afán, I., Davis, L.S., Chiaradia, A., 2017. Climate impacts on global hot spots of marine biodiversity. Sci. Adv. 3, 1–8. https://doi.org/10.1126/sciadv.1601198

Roxy, M.K., Ritika, K., Terray, P., Masson, S., 2014. The curious case of Indian Ocean warming. J. Clim. 27, 8501–8509. https://doi.org/10.1175/JCLI-D-14-00471.1

Ruttan, L.M., Gayanilo, F.C., Sumaila, U.R., Pauly, D., 2009. Small versus large-scale fisheries: a multi-species, multi-fleet model for evaluating their interactions and potential benefits. Artif. Intell. 1, 28–29.

Santos, R., 2007. A actividade pesqueira nos distritos de angoche , moma e pebane: uma caracterização preliminar. WWF, Maputo, Moçambique, 74 pp. http://www.biofund.org.mz.

Schaefer, K.M., 2001. Assessment of Skipjack tuna (Katsuwonus pelamis spawning actiity in the eastern Pacific Ocean. Fish. Bull. 99, 343–350.

Simões, F., 1984a. Investigação de recursos de tunideos em Moçambique de 1975 a 1984. Bol. Divulg. Inst. Investig. Pesqueira, Mozambique 6, 1–30.

Simões, F., 1984b. Recursos de atum nas águas de Moçambique. Rev. Investig. Pesqueira 9, 29–38.

Song, L., Zhou, J., Zhou, Y., Nishida, T., Jiang, W., Wang, J., 2009. Environmental preferences of bigeye tuna , Thunnus obesus , in the Indian Ocean : an application to a longline fishery. Environ. Biol. Fishes 85, 153–171. https://doi.org/10.1007/s10641-009-9474-7

Soto, M., Justel-Rubio, A., Lopez, J., 2016. Review of the Spanish Fish Aggregating Device Management Plan: Implementation, Evolution and Recommendations. 2nd ICCAT Work. Gr. FADs 53, 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Sumaila, U.R., Cheung, W.W.L., Lam, V.W.Y., Pauly, D., Herrick, S., 2011. Climate change impacts on the biophysics and economics of world fisheries. Nat. Clim. Chang. 1, 449–456. https://doi.org/10.1038/nclimate1301

Sumaila, U.R., Khan, A.S., Dyck, A.J., Watson, R., Munro, G., Tydemers, P., Pauly, D., 2010. A bottom-up re-estimation of global fisheries subsidies. J. Bioeconomics 12, 201–225. https://doi.org/10.1007/s10818-010-9091-8

Sumaila, U.R., Lam, V., Le Manach, F., Swartz, W., Pauly, D., 2016. Global fisheries subsidies: An updated estimate. Mar. Policy 69, 189–193. https://doi.org/10.1016/j.marpol.2015.12.026

Suzuki, R., Behera, S.K., Iizuka, S., Yamagata, T., 2004. Indian Ocean subtropical dipole simulated using a coupled general circulation model. J. Geophys. Res. C Ocean. 109, 1–18. https://doi.org/10.1029/2003JC001974

Swart, N.C., Lutjeharms, J.R.E., Ridderinkhof, H., De Ruijter, W.P.M., 2010. Observed characteristics of Mozambique Channel eddies. J. Geophys. Res. 115, 1–14. https://doi.org/10.1029/2009JC005875

Ternon, J.F., Bach, P., Barlow, R., Huggett, J., Jaquemet, S., Marsac, F., Ménard, F., Penven, P., Potier, M., Roberts, M.J., 2014. The Mozambique Channel: From physics to upper trophic levels. Deep. Res. Part II Top. Stud. Oceanogr. 100, 1–9. https://doi.org/10.1016/j.dsr2.2013.10.012

Tesfamichael, D., Pitcher, T.J., Pauly, D., 2014. Assessing Changes in Fisheries Using Fishers' Knowledge to Generate Long Time Series of Catch Rates: a Case Study from the Red Sea Evaluations of compliance with the FAO (UN) Code of Conduct for Responsible Fisheries View project Haida Gwaii ecosystem mod. Artic. Ecol. Soc. 19. https://doi.org/10.5751/ES-06151-190118

Tew-Kai, E., Marsac, F., 2010. Influence of mesoscale eddies on spatial structuring of top predators' communities in the Mozambique Channel. Prog. Oceanogr. 86, 214–223. https://doi.org/10.1016/j.pocean.2010.04.010

Tietze, U., 2016. Technical and socio-economic characteristics of small-scale coastal fishing communities, and opportunities for poverty alleviation and empowerment, Food and Agriculture Organizations of the United Nations. http://www.fao.org. FAO, Rome, Italy.

Torres-Irineo, E., Gaertner, D., Chassot, E., Dreyfus-León, M., 2014. Changes in fishing power and fishing strategies driven by new technologies: The case of tropical tuna purse seiners in the eastern Atlantic Ocean. Fish. Res. 155, 10–19. https://doi.org/10.1016/j.fishres.2014.02.017

Tremblay, M.-A., 1957. The Key Informant Technique: A Nonethnographic Application. Am. Anthr. 59, 688–701. https://doi.org/10.1093/fampra/13.1.92

Tyberghein, L., Verbruggen, H., Pauly, K., Troupin, C., Mineur, F., De Clerck, O., 2012. Bio-ORACLE: A global environmental dataset for marine species distribution modelling. Glob. Ecol. Biogeogr. https://doi.org/10.1111/j.1466-8238.2011.00656.x

Ullgren, J., Aken, H., Ridderinkhof, H., Ruitjer, W. de, 2012. The hydrography of the Mozambique Channel from six years of continuous temperature, salinity, and velocity observations. Deep Sea Res. Part I Oceanogr. Res. Pap. 69, 36–50. https://doi.org/https://doi.org/10.1016/j.dsr.2012.07.003

Underwood, A.J., 1997. A.J. Underwood, Experiments in ecology: their logical design and interpretation using analysis of variance, xviii, 504p. Cambridge University Press, 1996. Price £65·00 (£22·95 Paperback). J. Mar. Biol. Assoc. United Kingdom 77, 572–572. https://doi.org/10.1017/S0025315400072064

Venables, B., Hornik, K., Maechler, M., 2016. polynom: A Collection of Functions to Implement a Class for Univariate Polynomial Manipulations [WWW Document]. R Packag. version 1.3-8. URL https://cran.r-project.org/package=polynom

Wanyonyi, I.N., Wamukota, A., Mesaki, S., Guissamulo, A.T., Ochiewo, J., 2016. Artisanal fisher migration patterns in coastal East Africa. Ocean Coast. Manag. 119, 93–108. https://doi.org/10.1016/j.ocecoaman.2015.09.006

Wengraf, T., 2001. Qualitative Research Interviewing 1–425.

Wickham, H., 2009. ggplot2- Elegant Graphics for Data Analysis. Springer-Verlag New York, Houston-USA.

Wikle, C.K., Zammit-Mangion, A., Cressie, N., 2019. Spatio-Temporal Statistics with R, FL: Chapman & Hall/CRC. The R Series. Chapman & Hall/CRC The R Series, Boca Raton. https://doi.org/10.1201/9781351769723

Wood, S.N., 2006. Generalized Additive Models: An Introduction with R., Biometrics. https://doi.org/10.1111/j.1541-0420.2007.00905_3.x

Yen, K.W., Su, N.J., Teemari, T., Lee, M.A., Lu, H.J., 2016. Predicting the catch potential of skipjack tuna in the western and central Pacific Ocean under different climate change scenarios. J. Mar. Sci. Technol. 24, 1053–1062. https://doi.org/10.6119/JMST-016-0713-1

Zagaglia, C.R., Lorenzzetti, J.A., Stech, J.L., 2004. Remote sensing data and longline catches of yellowfin tuna (Thunnus albacares) in the equatorial Atlantic. Remote Sens. Environ. 93, 267–281. https://doi.org/10.1016/j.rse.2004.07.015

Zhang, J., 2016. Species association analysis. https://CRAN.R-project.org/ 32.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14. https://doi.org/10.1111/j.2041-210x.2009.00001.x

Zuur, A.F., Ineo, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer Sci. 2, 1–564. https://doi.org/10.1111/j.1467-985x.2010.00663_9.x

Supplementary Material (S)

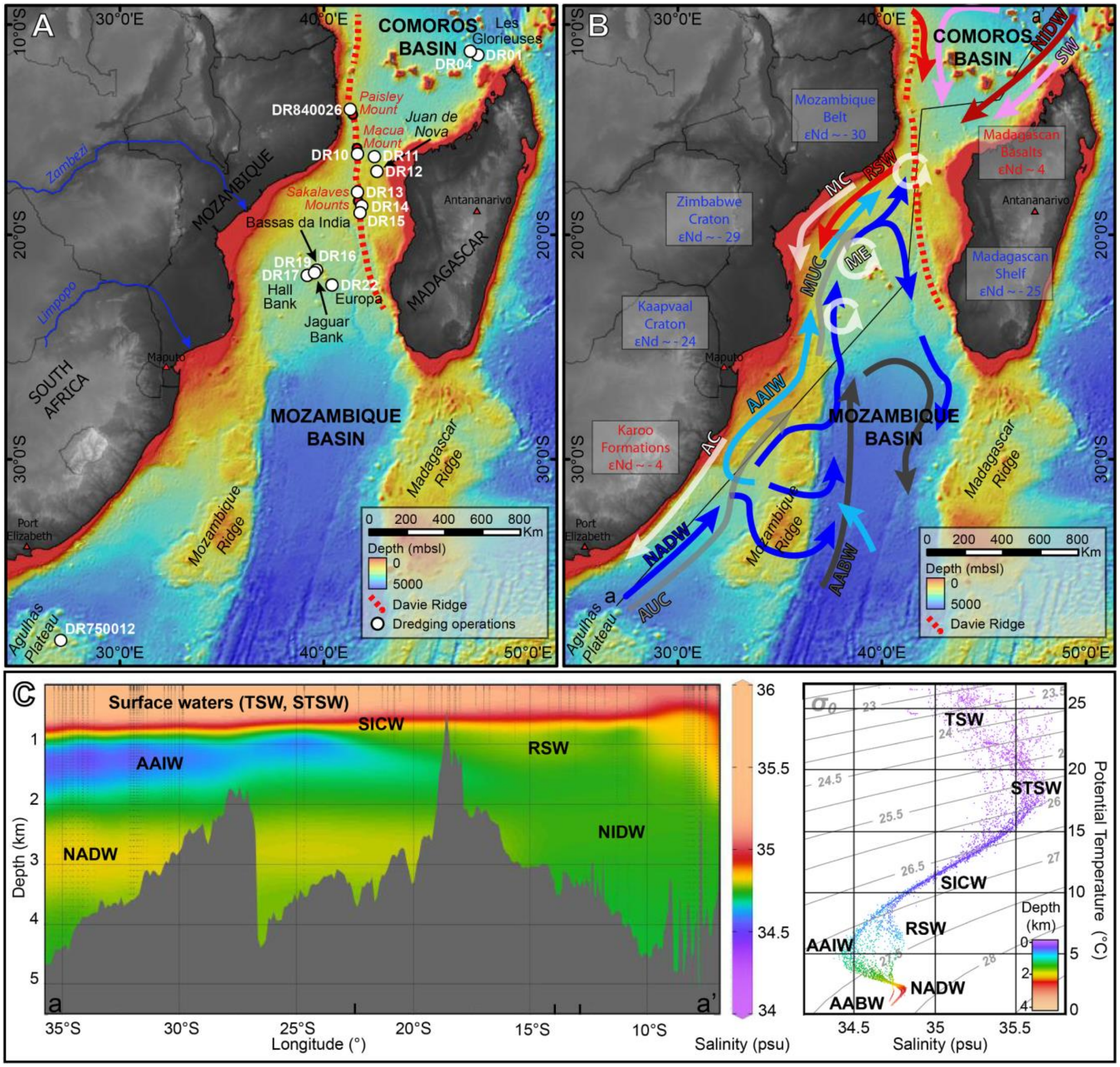


Figure S1. (A) Bathymetry of the Mozambique Channel (data from GEBCO and PAMELA cruises) with its main structures including the Davie Ridge and the Eparses Islands. The white dots represent the dredging operations. (B) Bathymetry of the Mozambique Channel (data from GEBCO and PAMELA cruises) showing the main circulation patterns AABW: Antarctic Bottom Water; AAIW: Antarctic Intermediate Water; AC: Agulhas Current; AUC: Agulhas Undercurrent; MC: Mozambique Current; ME: Mozambique Eddies; MUC: Mozambique Undercurrent; NADW: North Atlantic Deep Water; NIDW: North Indian Deep Water; RSW: Red Sea Water; SW: Surface Water including TSW: Tropical Surface Water, STSW: Sub-Tropical Surface Water and SICW: South Indian Central Water. The dark line corresponds to the section located in 1C. Nd isotope signatures (εNd) are presented for the main geological formations surrounding the channel (C) Salinity section showing the distribution of the main water masses present in the Mozambique Channel, based on Conductivity Temperature Depth (CTD) profiles (adapted by Charles et al., 2020).

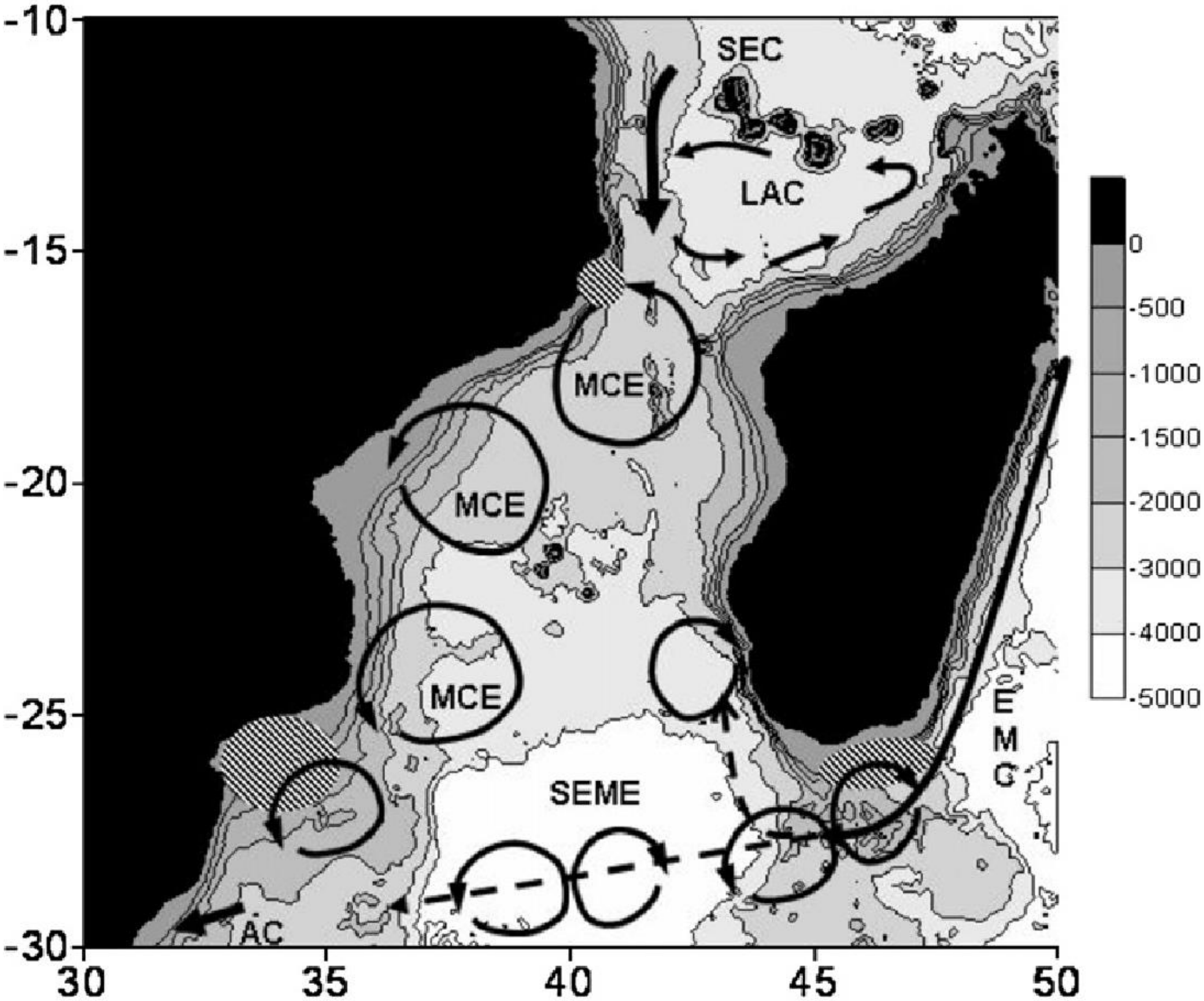


Figure S2. Major circulatory features in the Mozambique Channel with bathymetry. The main current and the mesoscale features are schematically shown. Hatched areas denote upwelling. In the north of the channel, the coastal current shown is fed by the South Equatorial Current (SEC) and later depicts a large anticyclonic cell in the Comoro basin. The white area with black points represents the lee eddy off Angoche. In the west, along Mozambique coasts, mesoscale eddies (MCE) move in a southwesterly direction. In the east coast of Madagascar, the feature shown is the East Madagascar Current (EMC) and in the south, the south east Madagascar dipolar eddies (SEME) moving westward and little north ward. The mesoscale eddies from the Mozambique channel and the dipolar structures from the south of Madagascar reach the Agulhas Current (AC) (author: Tew-Kai and Marsac, 2009).

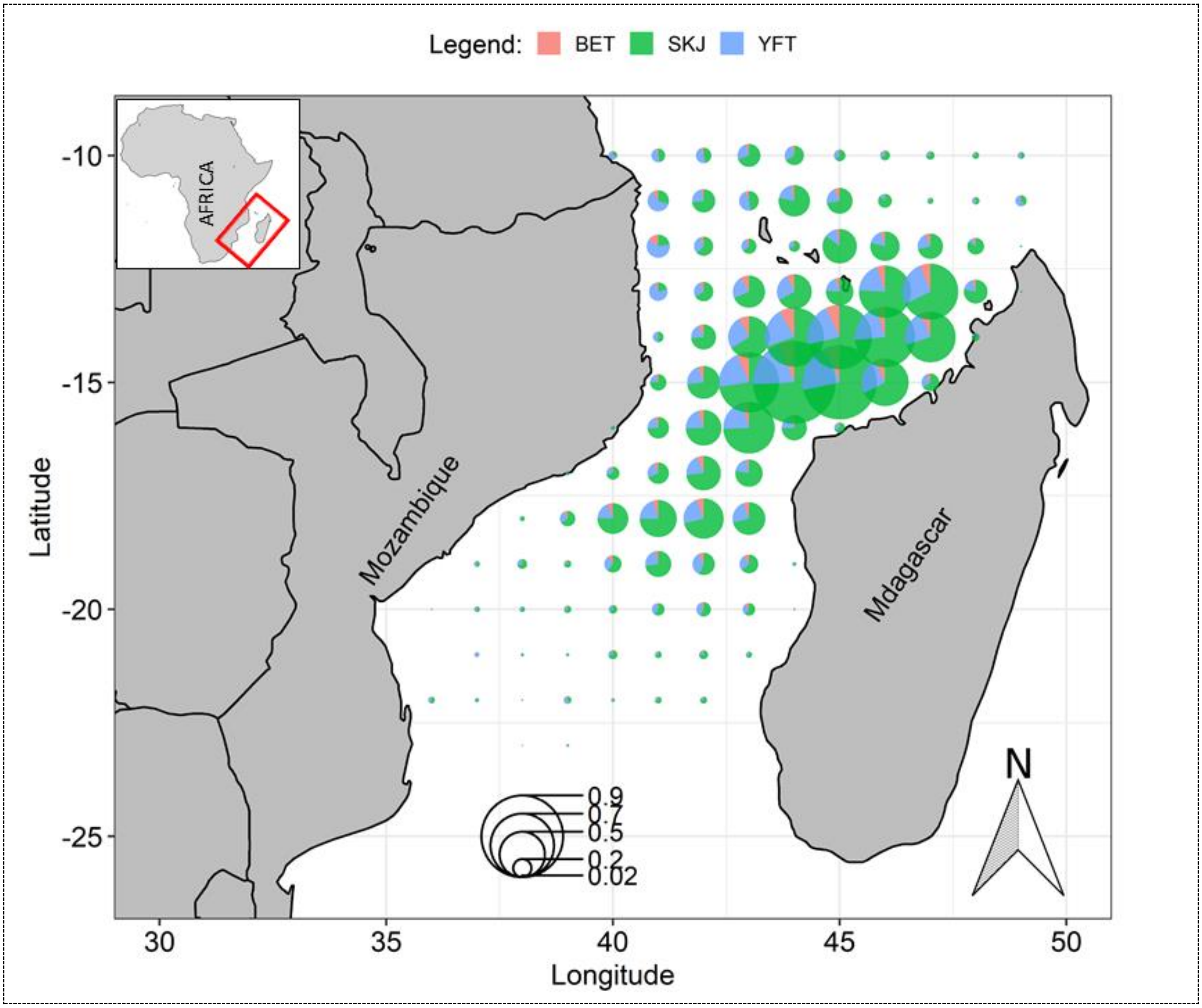


Figure. S3 - Map of study area with proportional distribution of tropical tuna (BET-bigeye tuna (*Thunnus obesus*), SKJ - skipjack tuna (*Katsuwonus pelamis*), and YFT - yellowfin tuna (*Thunnus albacares*)) caught by purse seine between 2003 and 2013. The circles in the bottom of the figure are proportional to the total catch.

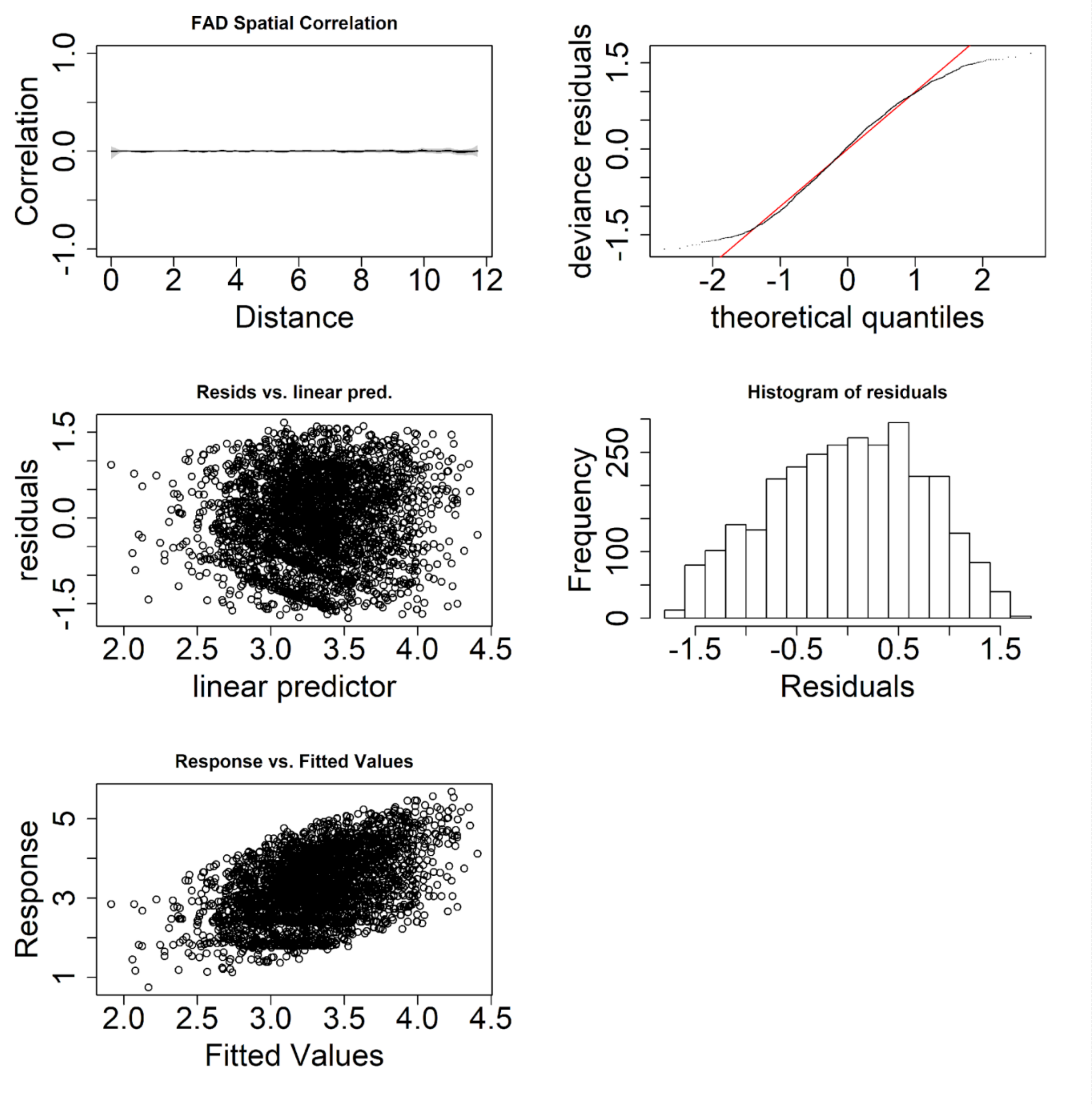


Figure S4- Display the goodness-of-fit for GAM in FADs. Top left panel depict spatial correlogram showing no spatial correlation, i.e., residual with non-significant autocorrelation. The mid panel in left sketched the homogeneity of variance, and the bottom left is closely to strait line. The two-right figures in the panel (qq-plot and histogram) shows how residual are close to normal distribution

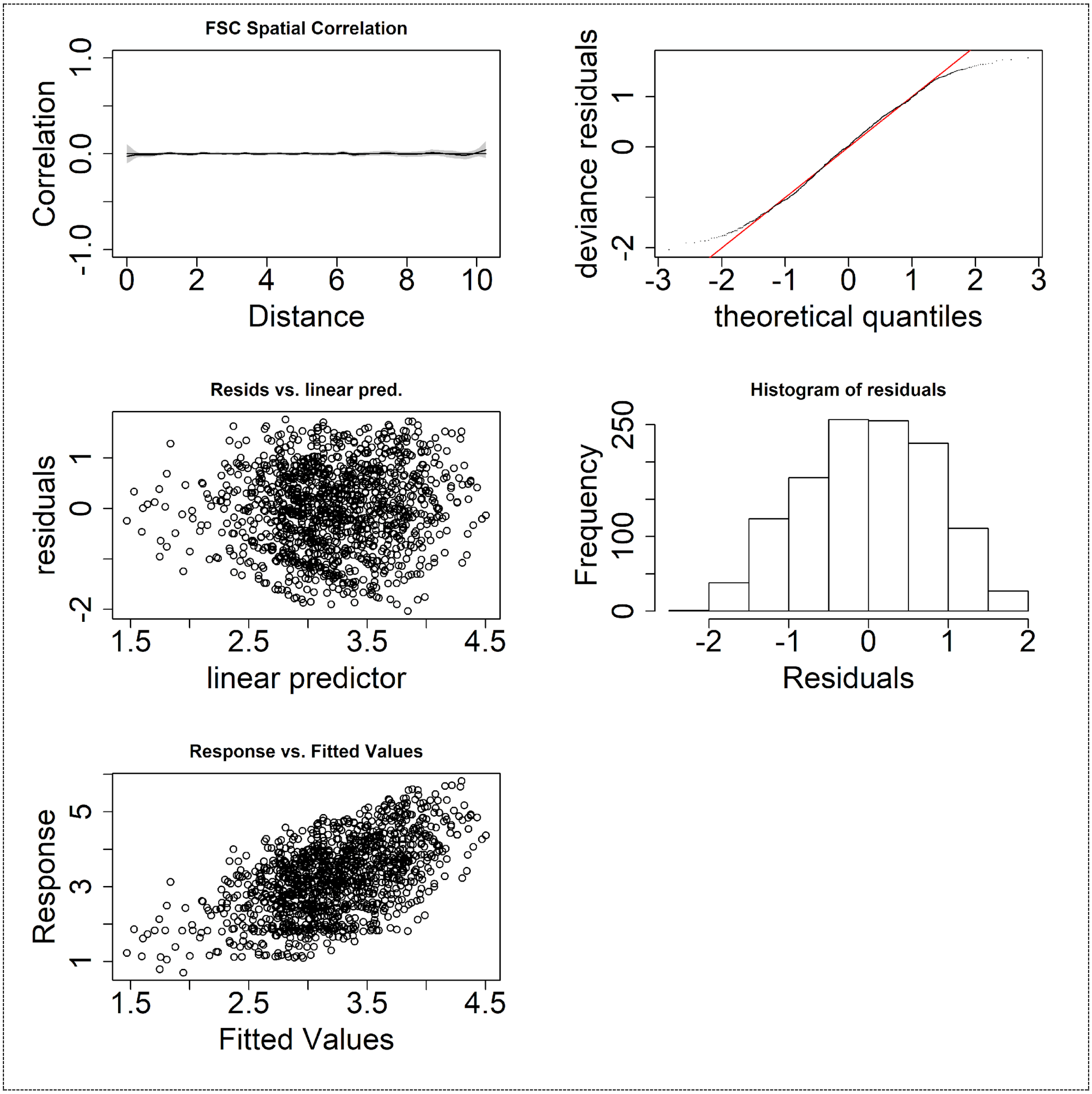


Figure S5- Display the goodness-of-fit for GAM in FSC. Top left panel depict spatial correlogram showing no spatial correlation, i.e., residual with non-significant autocorrelation. The mid panel in left sketched the homogeneity of variance, and the bottom left is closely to strait line. The two-right figures in the top and mid panels (qq-plot and histogram) shows residual close to normal distribution

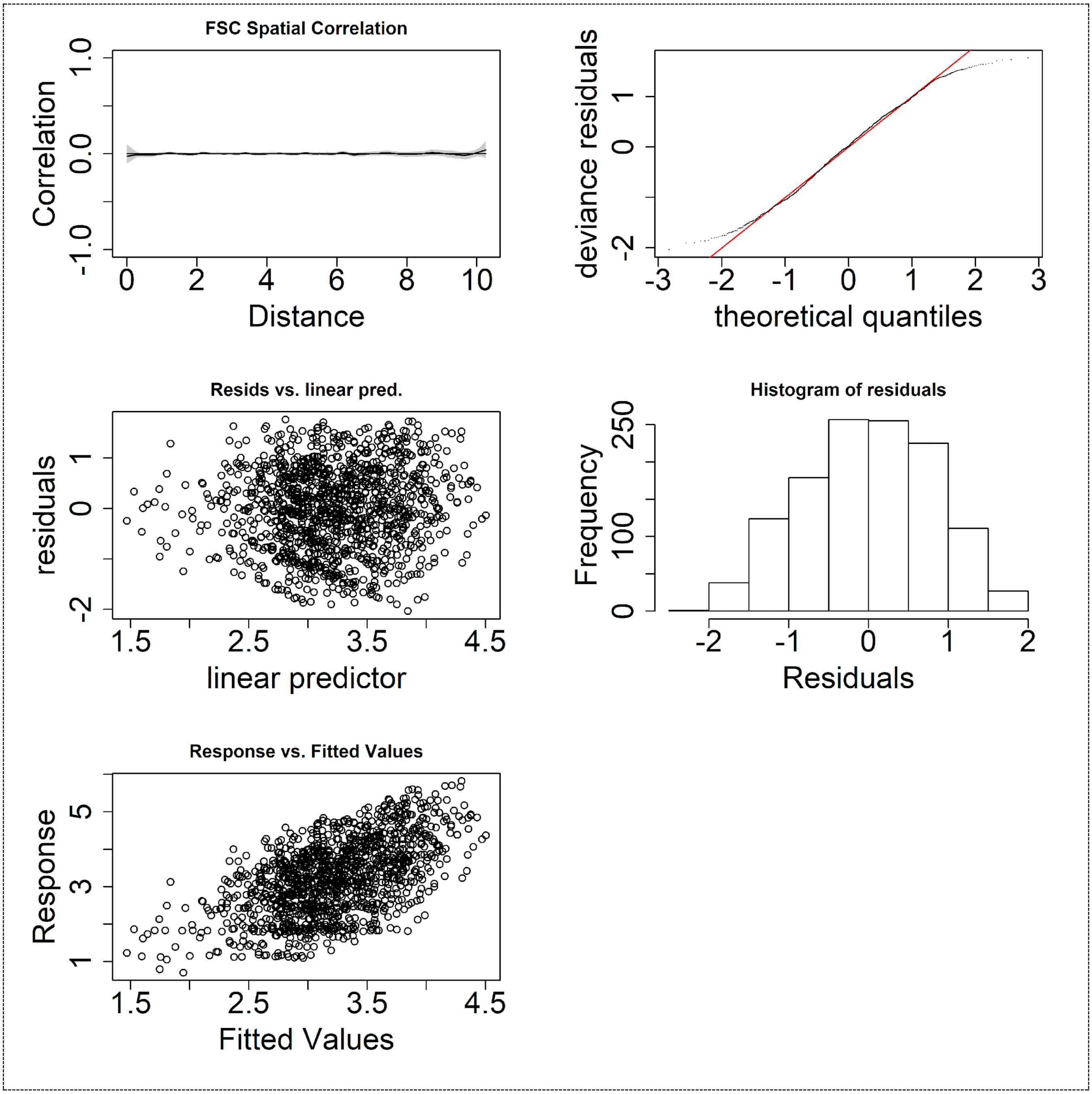


Figure S6 - Display the goodness-of-fit for GAM from SKJ. model Top left panel depict spatial correlogram showing no spatial correlation, i.e., residual with non-significant autocorrelation. The mid panel in left sketched the homogeneity of variance, and the bottom left is closely to strait line. The two-right figures in the panel (qq-plot and histogram) shows residual close to normal distribution.

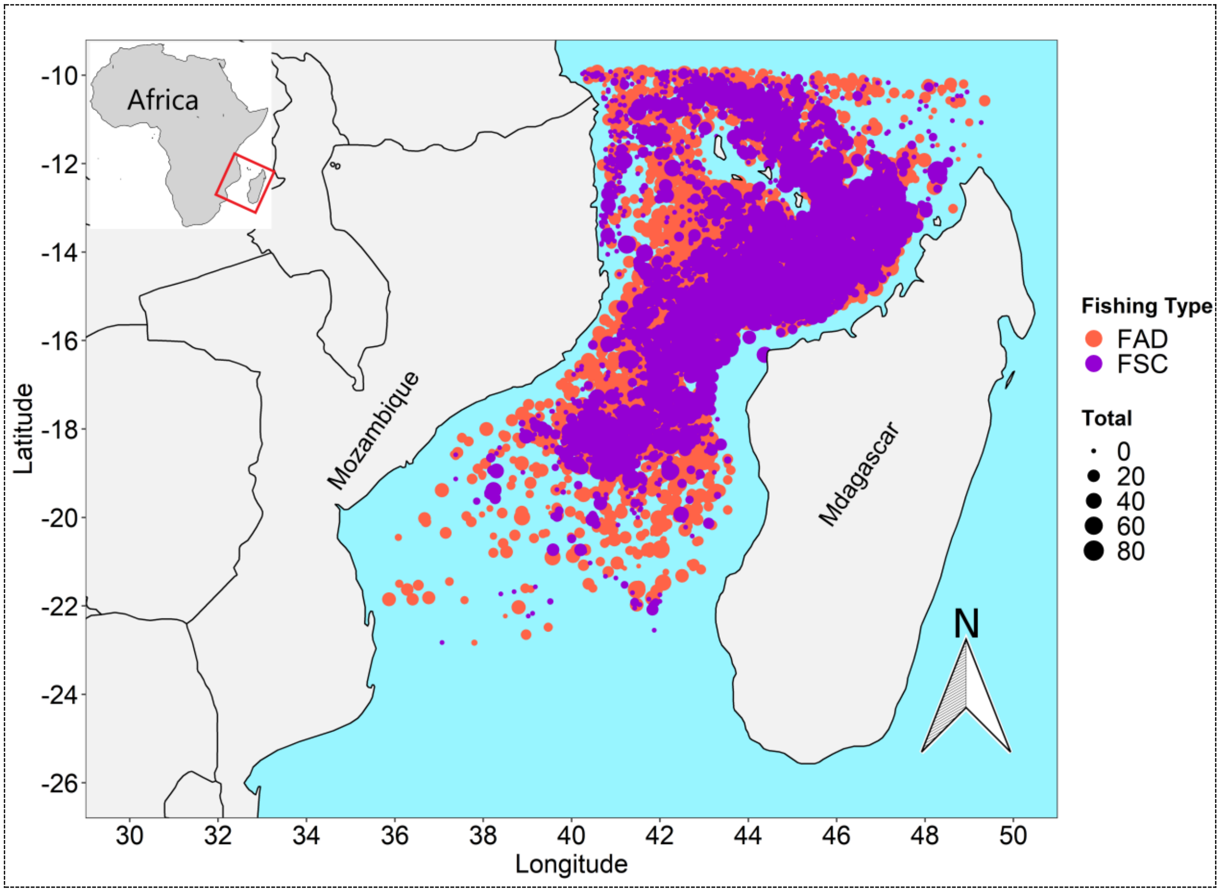


Figure S7 - Catches distribution of Skipjack tuna (tonnes) in the Mozambique Channel targeted by Spanish purse seine fleets for the period 2003 - 2013 (RPS). Catches were aggregated monthly by 0.25º x 0.25º resolution. FSC - Free-Swimming Schools; FAD - Fish Aggregating Devices.

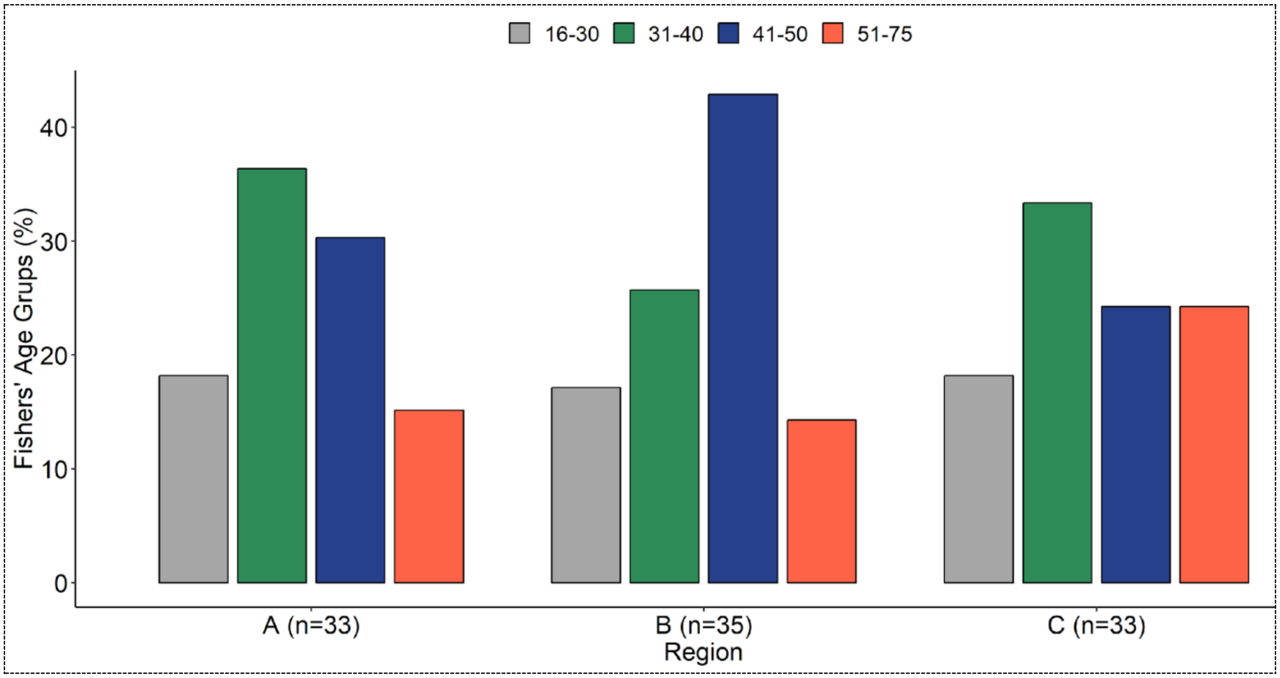


Figure S8 - Age frequency distribution for the interviewees by region. Region A and B - for the villages located in northern part of Mozambique (Cabo Delgado and Nampula provinces), C- sampled villages in southern part of the country (Inhambane and Maputo provinces). The *n* values in the brackets of regions A, B, and C correspond to the interviewed fishers in visited villages.

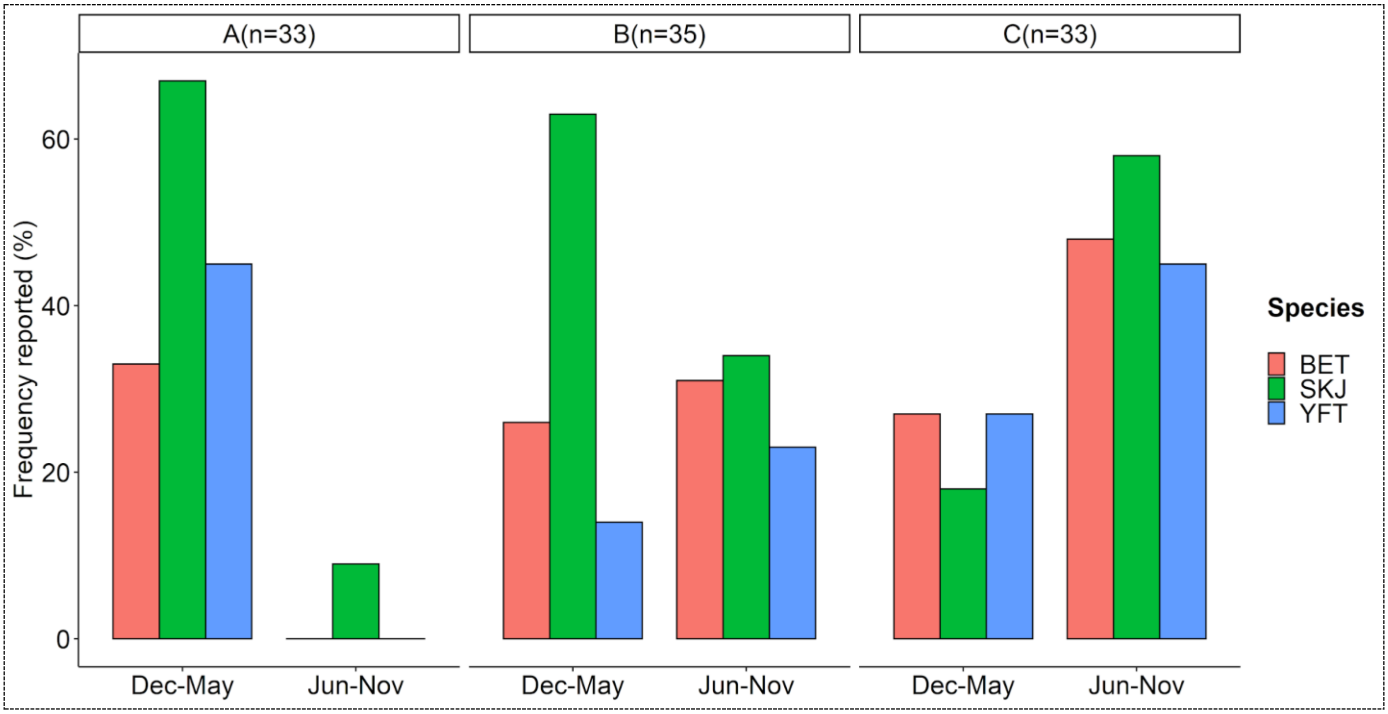
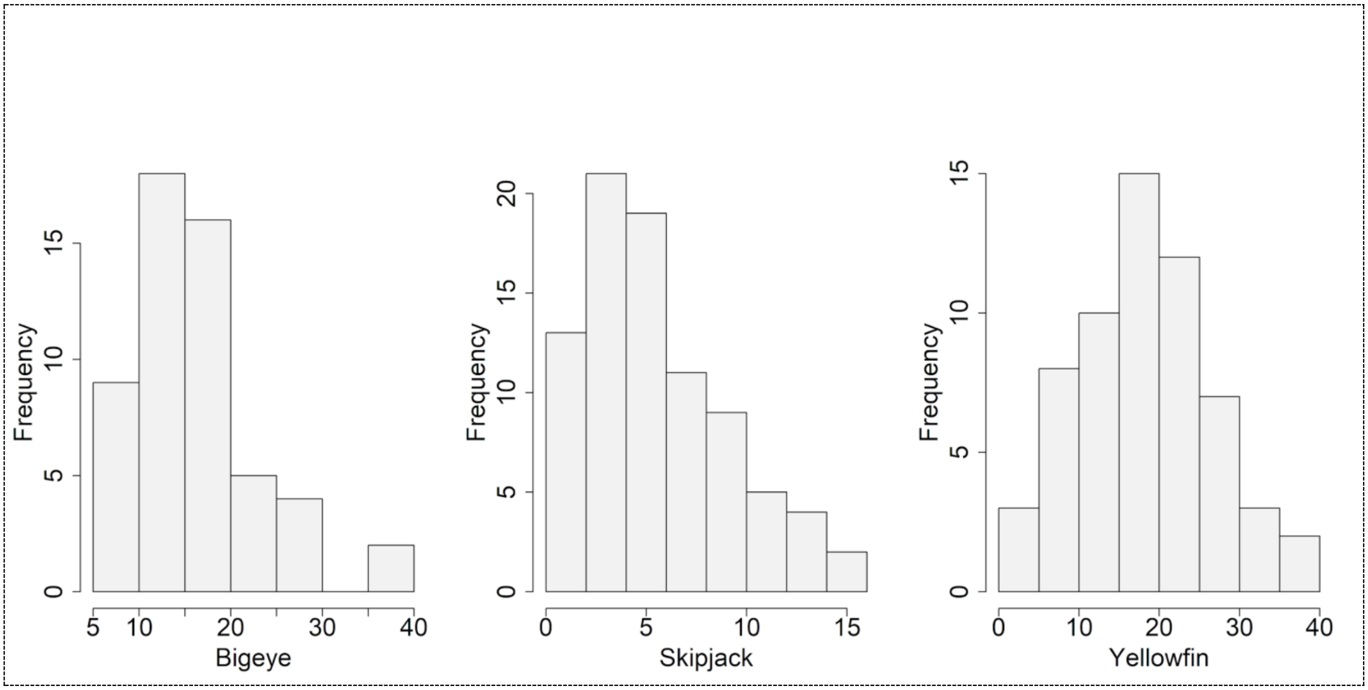


Figure S9 - Frequency of occurrence reported for each tropical tuna species for each season per region. A (northernmost, n=33 interviewed fishers), B (center-north, n=35), and C (southern, n=33) are the sampled regions. BET-Bigeye tuna, SKJ- Skipjack, and YFT-Yellowfin tuna.



FigureS10. Frequency of average weight in kilos of regular catches for tropical tuna species reported by small-scale.

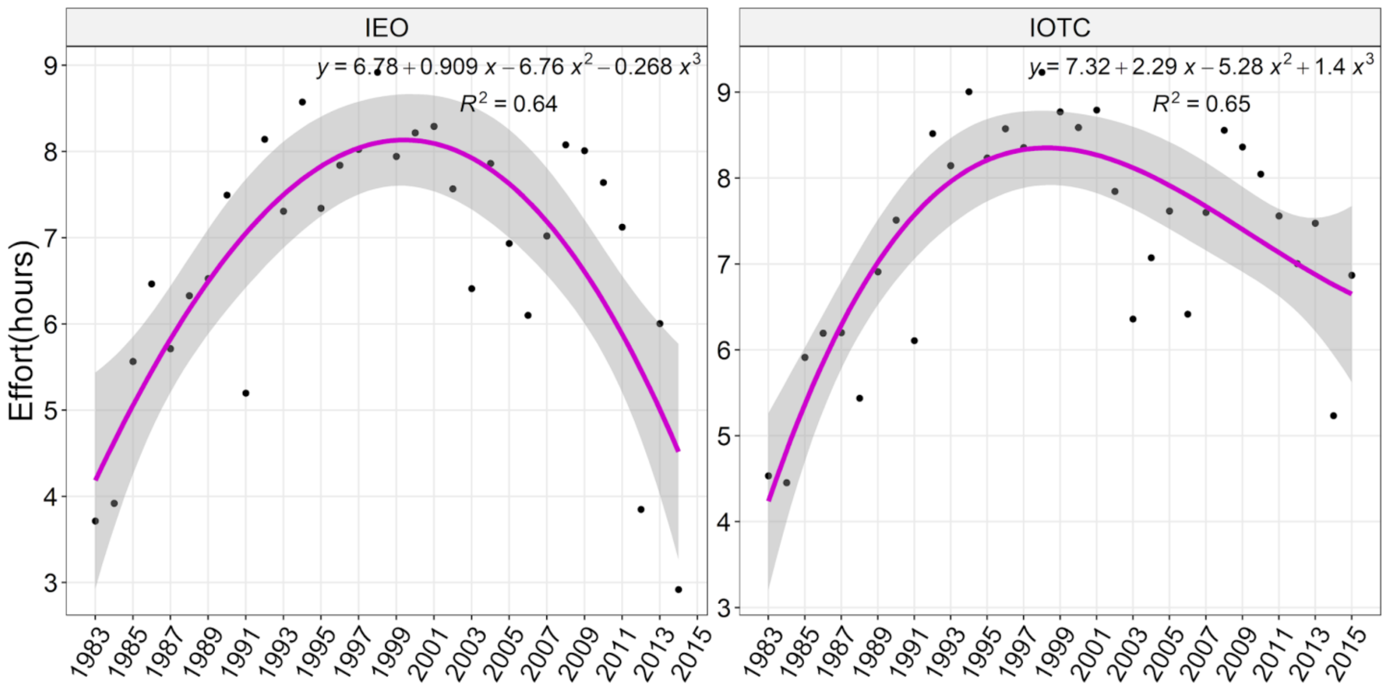


Figure S11. Evolution of fishing effort in hours transformed to the logarithm scale in Mozambique Channel for the period 1983 - 2014.

Table S1 - Environmental, spatial and temporal variables used in the study

Variables	Acronym Used	Unit	Spatial Resolution	Temporal Resolution	Product identifier
Chlorophyll a concentration	CHL	mg m^{-3}	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_BIO_001_029
Chlorophyll Gradient concentration	CHLGD	mg m^{-3}	0.25º x0.25º	±7 days	GLOBAL_REANALYSIS_BIO_001_029
Current Heading	HDG	degrees	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_PHY_001_031
Eddy Kinetic Energy	KE	m^2 s^{-2}	0.25º x0.25º	Daily	Derived from model
Current Velocity	SSC	m s^{-1}	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_PHY_001_031
Sea Surface Height	SSH	m	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_PHY_001_031
Oxygen concentration	O_2	mg l^{-1}	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_BIO_001_029
Sea Surface Salinity	SSS	g kg^{-1}	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_PHY_001_031
Sea Surface Temperature	SST	ºC	0.25º x0.25º	Daily	GLOBAL_REANALYSIS_PHY_001_031
Sea Surface Temperature Gradient	SSTGD	ºC	0.25º x0.25º	±7days	GLOBAL_REANALYSIS_PHY_001_031
Latitude	Lat	degrees	0.25º x0.25º	Daily	-
Longitude	Long	degrees	0.25º x0.25º	Daily	-
Month	Month	-	0.25º x0.25º	Monthly	-
Natural Day (365 days per Year)	YearDay	-	0.25º x0.25º	Daily	-
Year (2003 -2013)	Year	-	0.25º x0.25º	Yearly	-

Questionnaire applied for data collection with small-scale fishers through face-to-face interview

Data____/___/____; Place_____________________

Part -I: Bio-Data

Date of Birth/Age______________ Year Start to Fish/Fishing years: ___________

Fishing years in this village: ______ Fish years in Other Villages: _______________

Interviewee Occupation: Crew ( ) Ownership ( ) Others__________________

Did you change occupation? No ( ) Yes ( ) ; If yes when? _______________

Education level _________________________ Gender: Female ( ) Male ( )

Do you do other jobs besides fishing? ____

Part- II: Environmental Aspect

1. **Do you catch or have been catching the following tuna species in this village?**

Skipjack ( ) Yellowfin ( ) Bigeye ( ) Others tunas(specify)________________

1.1 Which months of high and low tuna abundance on catches?

High abundance ________________, Low abundance_____________________

1.2 **What is the average size of the individual tuna do you caught usual per day/month?**

Season	**Yellowfin**			**Bigeye**			**Skipjack**		
	Kg	**Nº**	**Lcm**	**Kg**	**Nº**	**Lcm**	**Kg**	**Nº**	**Lcm**
March-May									
Jun-Aug									
Sept-Nov									
Dec-Fev									

2. **About the equipment and effort devoted to catch tuna.**

2.1 What was the best effort of tuna catches in the firsts 5 years when you start to fish?

Nº of size crew_____________ Nº of trips (days) _______________

Type of gear used________________________

2.2 What is the average catch of tuna in the last 5 years? ___________________

2.3 What is the largest tuna you have been caught or seen in your life?

Size in centimetres________________ Weight in Kilos ______________

When did this happen? ________________, Where_____________________

3. **Can you tell us about the equipment and effort devoted to catch tuna?**

4.1 What type of boat do you use to catch tuna?
Fibber with engine ( ) Wooden Sail/rowing boat ( ) Wooden boat outboard engine ( )
Canoe rowing/sail ( ) Other types (specify) ________________________

4.2 What is the boat/canoe size and size crew?

Size in meters (please specify): ______________,
Nº of permanent size crew _________, Nº of seasonal size crew___________, Other___________

4.3. What is the gear type used to catch tuna?

Local purse seine ( ) Longline ( ) Pole and line ( ) Gill net ( ) Line and hook ( )

Size of gear ____________

4.4 **How do you detect tuna schools?**
Direct observation ( ) Birds as indicators ( ) Binocular ( )
FADs ( ); specify FAD type please: ____________ Others (Specify)_______________

4.4 **How many hours do you spend working to catch tuna per season as full time (FT) or part time (PT)?**

Working hour per season	March-May		Jun-Aug		Sept-Oct		Nov- Dec	
	FT	PT	FT	PT	FT	PT	FT	PT
Travel hours to fishing ground (leave-arrive)								
Retuning hours to landing site (leave-arrive)								
Estimated fishing hours per day								
Nº of trips per week								
Estimated fishing days per month								
Estimate distance to fishing ground (Km)								
Hours of net repairing/maintenance								
Hours of boat repairing/maintenance								
Hours of selling fish								

4. **Is there any restriction type on tuna fish or bycatch species in this area?**
None ( ) Yes ( )

If yes, please tell us: restriction types_______, year started_____ Are you satisfied ( ) Not satisfied ( ) Any comments about restriction__________________________________

6. **Does the occurrence of tuna increased or declined?**
Between 2005- 2009______________________
Between 2010 -2014______________________

7. **Is tuna easier to catch in the last 2 years?**
Yes, why_______________
No, why_______________

8. **What is the best period of the day to catch tuna in this area?**

Sunrise (   )   Daytime (   ) Sunset ( )   Night-time ( )   No differences ( )

Part III- Socioeconomic Aspect and Chain Connections

9. **What are the destination of landed tuna fish?**

Feed the crew members ( )   Local middlemen (   )   restaurant (   )   retailers (   ) traders ( )   consumers (   )   others (specify)__________

10. **How did you usual sell the fish?**

Fresh fish (   )   Fresh fish on ice (   ) Frozen fish (   ) Others (specify)______________

11. How much do you sell a kilo of the following species according?

Skipjack _____________   Yellowfin______________   Bigeye_______________

12. **Do you know where the buyers come from or taking to the fish?**
National citizen (   ), citizen from neighbour country (   )
Fish are sold local (   ) fish are taken to abroad (   ) I do not know (   )

13. **Which gender usual come to buy tuna fish for business?**
Female (   )   Male (   )   Both female and male (   )
Do you know why is it so? ___________

14. **From your experience, what is the total cost for fishing?**
14.1 Daily cost or fishing trip cost
Fuel and __________   oil ______________   Ice___________
Bait_____________ , Food ___________Others _______________; Do not know ______

14.2 **Annual coast**
Boat license _________, fishing gear license_________, Boat maintenance _________,
fishing gear maintenance___________ Do not know ____________;

;

15. **Can you tell us the cost of your fishing equipment?**
Boat /canoe____________________, size___________, type_________
Boat engine ___________________, size _______
Pole______, hook_______, line_______, Pole size_____, hook size_____, line size_____
Traditional seine______________, size___________; Do not Know__________

16. Where did you get the supply fishing equipment and materials?

17. **How do you share or divide the profits from fishing with all members?**
____
____

18. **In average how much do you earn in good and worst season of tuna abundance?**
March- May_________________, June - August __________________

September- November ____________, December - February____________

Part III- Interaction with Industrial Fishing Vessels

20. Have you ever seen industrial tuna fleets in your fishing ground?
Yes ( ) No ( ) Other type of industrial fishing vessel ( )

What type of gear do they use?___________________________

Which species are targeting? Tuna species ( ) Other species ( ) specify ______________________

There is any problem caused by industrial fleets? Yes ( ), No ( ); if yes specify the problems___ ____ _

21 About the use of FADs by small-scale fisheries. Questions 21.2 -21.5 will proceed if the answer from 21.1 is positive (yes).

21.1 Do you use FADs? Yes ( ) No ( ) If yes; since when?________

21.2 What types of FADs do you use? Anchored FADs ( ) Drifting FADs ( ) Nº of FADs______

21.3 Is the use of FADs seasonal? Yes ( ) No ( )
If yes; please specify the season_____________________________

21.4. Do use of FADs increase or decrease your catches?
Increase the catches ( ) Decrease the catches ( ) No change in catches ( )

21.5 What is the attraction area of FADs? (1 nm≈2Km)
< 3nm_____; 3 - 5nm_______; 5-10 nm_______; >10 nm____________

22. Do drifting FADs arrive to your coast? Yes ( ) No ( )
If yes, Where?_________________

Which season? _________________

How many FADs annually? __________________

23. Did the number of FADs encountered in your area changed in the last 10 years?

Increased ( ) Decreased ( ) Number of FADs__________