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Ahmed Riyaz Jauharee

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE L'UNIVERSITÉ DE MONTPELLIER

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Unité de recherche : Marine Biodiversity, Exploitation & Conservation (MARBEC)

The tuna pole and line FAD (fish aggregating device) fishery of the Maldives: towards science-based management through fishers and scientific knowledge

La pêche au thon à la canne autour des dispositifs de concentration de poissons (DCP) aux Maldives: vers une gestion fondée sur la science grâce aux connaissances scientifiques et celles des pêcheurs

Présentée par Ahmed Riyaz JAUHAREE
Le 11 Février 2022

Sous la direction de Laurent DAGORN

Devant le jury composé de

Pascale CHABANET, Directrice de Recherche, IRD, UMR ENTROPIE	Présidente du jury
Frédéric MENARD, Directeur de Recherche, IRD, UMR MIO	Rapporteur
Gala MORENO, Consultante en pêcheries durables	Rapporteur
Laurent DAGORN, Directeur de Recherche, IRD, UMR MARBEC	Directeur

UNIVERSITÉ DE MONTPELLIER

Dedication

This thesis is dedicated to my parents who did their very best, even during difficult times, to ensure we could have a wonderful life.

Acknowledgements

Alhamdhulillah

This achievement marks a beginning of a new adventure in my quest to seek and spread knowledge among society. I have always enjoyed sharing knowledge with both young and mature across my nation. As a child I always look forward to seeing what my father has caught every time he goes out fishing. I can still remember, the first thing I do (soon after waking up in the morning) was to rush outside to see what my father has caught that night. He would hang the catch on a tree just outside our home. As I grew older, I went out fishing with him sometimes out on a boat and sometimes to the shore along the island where I live – Male'. The last time we went out on Male', we were only able to catch a gunny sack and an old shoe. Since then, we stopped going to the shore along Male', but I continued to go out fishing with him and with my friends on boats and to other islands too. This incident made me think why fish was no longer biting like before along our shore.

After completing my basic education, I got the opportunity to work at the Education Development Centre as a curriculum developer for Fisheries Science. This provided me an opportunity to visit all the atolls of the Maldives and interact with students, teachers and fisher communities. It helped me study, write and share fisheries knowledge among the communities. In addition, I got the opportunity to take part in fishing activities and learn from fishers as they share their experiences making me aware of the changes in fisheries over the years. Looking at the fishers issues from a scientific perspective helped me better understand and relate these issues to their practices, ecosystems and changes that were occurring in the wider world. These interactions with fishers helped enrich my knowledge of the Maldives fisheries and I am very thankful to all those fishers who shared their experiences with me.

It is a challenge to write a compressive acknowledgement. To ensure I do not miss out on any of those who helped me achieve this thesis, I would start by sincerely saying a very big THANK YOU to all of them. This research project that I began in 2017 would not have been possible without the support and cooperation from several people. First, I thank International Pole and Line Foundation (IPNLF) and its founding trustee Mr. John Burton for providing all the funding necessary for this project. Dr M Shiham Adam, who is also representing IPNLF Maldives, deserves a big thank you for his positive impacts on my career. It was he who introduced me to fisheries research by recruiting me to Maldives Marine Research Centre in 2008 and consistently supporting me to excel in my career.

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Abstract

Maldivians have sustainably been exploiting tuna using hook and line in the Indian Ocean for over a millennium, with 20% of the total Indian Ocean tuna catches currently landed in the Maldives. After four decades using on average 55 anchored fish aggregating devices (AFADs) spread over the entire archipelago, this thesis aims to improve our knowledge on the fishery ecology of tuna within the Maldivian AFAD array in order to better understand the drivers of the sustainability of the fishery for the coming years. The ecology of tuna around these AFADs was studied by collecting local ecological knowledge from 54 pole and line fishers and by acoustically tagging 65 skipjack and 57 yellowfin tuna within an instrumented 21-AFAD array. Most fishers consider that slight currents, suitable sea temperature, prey and attractants enhance the aggregations while strong currents, high sea temperatures and stormy conditions make tuna leave AFADs. They also consider that tuna tend to stay associated with AFADs 3 to 6 days, which is comparable to results from acoustic tagging (from 2 to 5.5 days on average). Acoustic tagging showed that tuna do not have a specific preference in the direction of movement, and very few fish moved from one FAD to another. Therefore, the 55 AFADs in the Maldives do not act like a network but appear to be relatively independent. The Maldives FAD network can be considered as a case study to examine the pros and cons of sparse FAD networks as supports for fisheries, while minimizing potential negative impacts. More research on the ecological, social and economic aspects of the pole and line fishery must be conducted to support the Maldives in their science-based management.

Keywords: Anchored Fish Aggregating Device, Tropical tunas, Pole and Line, Maldives, Local Ecological Knowledge, Residence Time.

Résumé

Les Maldiviens exploitent durablement le thon dans l'océan Indien depuis plus d'un millénaire, avec 20% des captures totales de thon de l'océan Indien actuellement débarquées aux Maldives. Après quatre décennies d'utilisation d'une moyenne de 55 dispositifs de concentration de poissons ancrés (DCPA-) répartis sur l'ensemble de l'archipel, cette thèse vise à améliorer nos connaissances sur l'écologie de la pêche au thon au sein du réseau de DCP des Maldives afin de mieux comprendre les moteurs de la durabilité de la pêche pour les années à venir. L'écologie du thon autour de ces DCP a été étudiée en recueillant les connaissances écologiques locales de 54 pêcheurs à la canne et en marquant acoustiquement 65 listaos et 57 albacores dans un réseau de 21 DCP instrumentés. La plupart des pêcheurs considèrent que des courants faibles, une température de la mer adaptée, des proies et des attractifs favorisent les agrégations tandis que des courants forts, des températures de la mer élevées et des conditions orageuses font que les thons quittent les DCP. Ils considèrent également que les thons ont tendance à rester associés aux DCP de 3 à 6 jours, ce qui est comparable aux résultats du marquage acoustique (de 2 à 5,5 jours en moyenne). Le marquage acoustique a montré que les thons n'ont pas de préférence spécifique dans la direction du mouvement, et que très peu de poissons se déplacent d'un DCP à l'autre. Par conséquent, les 55 DCP des Maldives ne fonctionnent pas comme un réseau mais semblent être relativement indépendants. Le réseau de DCP des Maldives peut être considéré comme une étude de cas pour examiner les avantages et les inconvénients des réseaux de DCP peu denses comme supports pour les pêcheries, tout en minimisant les impacts négatifs potentiels. Des recherches supplémentaires sur les aspects écologiques, sociaux et économiques de la pêche à la canne doivent être menées pour soutenir les Maldives dans leur gestion basée sur la science.

Mots clés: dispositif de concentration de poissons ancré, thons tropicaux, canne et ligne, Maldives, connaissances écologiques locales, temps de résidence

Résumé substantiel (French extended abstract)

Introduction

En raison de l'importance des captures, de la valeur économique et du commerce international, sept espèces de thon sont considérées comme plus importantes - le listao (*Katsuwonus pelamis*), l'albacore (*Thunnus albacares*), le patudo (*Thunnus obesus*), le germon (*Thunnus alalunga*), le thon rouge de l'Atlantique (*Thunnus thynnus*), le thon rouge du Sud (*Thunnus maccoyii*) et le thon rouge du Pacifique (*Thunnus orientalis*). Les captures mondiales de thon ont continuellement augmenté au fil des ans pour atteindre 7,9 millions de tonnes en 2018 (SOFIA, 2020). Si la pêche au thon est faite à partir de plusieurs engins de pêche, près de 66 % des captures mondiales de thon sont faites uniquement par des thoniers senneurs.

Dans l'océan Indien, les captures de thon tropical n'ont cessé d'augmenter depuis les années 1980 et l'arrivée dans cet océan des thoniers senneurs. Cet océan abrite la deuxième plus grande pêcherie de thon au monde (SOFIA, 2020) avec 21 % des captures mondiales de thon (ISSF, 2021), l'océan pêchant le plus de thon étant l'océan Pacifique Ouest. Bien qu'il existe plusieurs espèces de thon dans l'océan Indien, quatre espèces principales contribuent principalement aux captures totales de thon dans cet océan : le listao, l'albacore, le patudo et le germon. Les captures de thon de l'océan Indien ont atteint un pic en 2005 avec 1,2 million de tonnes. Le listao et l'albacore représentent la majeure partie des captures avec en moyenne près de 90%, la plupart des prises étant débarquées par les thoniers senneurs (43 %) (CTOI, 2021). Les Maldives, pays côtier dans l'océan Indien, contribuent à environ 20 % des captures de thon de l'océan Indien et sont ainsi le 2ème pays pêcheur de thon de cet océan (CTOI, 2020).

Le thon est pêché aux Maldives depuis plus d'un millénaire (MMRB 2, 1996) en utilisant des techniques de pêche à bases d'hameçons (principalement la canne, la ligne à main et la traîne). Cette pêche a assuré la subsistance de tous les habitants de l'archipel pendant des siècles, fournissant une source de protéines et une importante opportunité d'emploi dans les îles extérieures où les activités économiques étaient limitées. Sous l'impulsion du gouvernement et l'implication du secteur privé, au cours des 50 dernières années, la pêche au thon aux Maldives est passée d'une pêche de subsistance traditionnelle à une pêche commerciale plus moderne destinée à l'exportation. Le thon est ainsi le principal produit d'exportation depuis la fin du 20ème siècle, avec 105 000 tonnes de thon exportées par les Maldives en 2020 (NBS, 2021).

L'association des thons aux objets flottants (appelés "oivaali") était connue depuis plusieurs siècles par les pêcheurs maldiviens qui recherchaient les billes de bois qui dérivaient à proximité des atolls pour pêcher du thon. Suivant l'émergence des DCP ancrés (bouées fabriquées par l'Homme et ancrées près des côtes) dans les années 1980 dans les différents océans, les Maldives ont investi dans ces outils d'aide à la pêche dès le début. Dans l'océan Indien, les DCP ancrés sont utilisés dans plusieurs pays dont l'Indonésie, les Philippines, les Maldives, Maurice, les Comores et La Réunion. Dans certains pays comme les Philippines et l'Indonésie, les réseaux sont composés de plusieurs centaines voire milliers de DCP ancrés, tandis que dans d'autres (par exemple les Maldives, Maurice, les Comores, La Réunion), les réseaux sont composés de quelques dizaines de DCP. Les réseaux de DCP ancrés sont soit financés et entretenus par les gouvernements nationaux (par exemple aux Maldives, à Maurice et La Réunion), soit déployés par des particuliers ou des entreprises privées, sans coordination gouvernementale (par exemple, en Indonésie). Lorsqu'un gouvernement décide de financer un dispositif de DCP ancrés, l'objectif est clairement d'assurer la sécurité alimentaire et de soutenir la pêche au thon locale, en facilitant l'accès aux thons. Cet objectif est atteint en augmentant l'accessibilité à la ressource pélagique et en réduisant le coût de recherche et/ou en facilitant les captures de poissons pélagiques.

Les Maldives sont passés progressivement d'un premier réseau de DCP ancrés expérimental au début des années 1980 à un réseau de 55 DCP ancrés, toujours maintenu actuellement. Les DCP sont localisés tout autour de l'archipel des Maldives, permettant aux pêcheurs d'y accéder facilement, non loin de leurs ports d'attache. Ce développement a contribué à ce qu'environ un tiers du thon débarqué aux Maldives provienne des DCP ancrés (Miller, et al., 2017). Contrairement à de nombreux autres pays qui utilisent les DCP, les distances entre les DCP voisins aux Maldives sont considérablement plus grandes (25 à 48 km) que dans d'autres pays (de l'ordre de 15 à 20 km en moyenne).

L'évolution de la pêcherie au cours des dernières décennies, dans le contexte du changement global et de l'évolution de la pêcherie de thon dans l'Océan Indien, pose légitimement la question de sa durabilité. A cette fin, il est important de mieux comprendre les composantes clés de la pêche thonière maldivienne, d'examiner et de comprendre le rôle des DCP ancrés dans la stratégie de pêche et les performances de la pêche à la canne maldivienne. En outre, il était également crucial d'acquérir des connaissances sur l'écologie comportementale du thon, qu'il s'agisse du listao ou de l'albacore (les deux espèces les plus fréquemment capturées), et d'étudier le fonctionnement du réseau de DCP ancrés. Enfin, impliquer les pêcheurs dans la recherche, en collectant et reconnaissant leurs savoirs locaux, était également un objectif important de la thèse.

Objectifs de la thèse

L'objectif principal de la thèse est d'améliorer nos connaissances sur l'écologie des thons aux Maldives et sur les rôles que joue le réseau de DCP dans les performances, et éventuellement la durabilité, de cette pêcherie. Notre approche consistait à utiliser des sources de données complémentaires, telles que le marquage électronique (télémétrie acoustique) des thons et les connaissances écologiques locales. Plus précisément, les deux principaux objectifs de cette recherche étaient les suivants :

a) Examiner le fonctionnement et l'évolution de la pêche à la canne des Maldives et mieux comprendre le rôle des DCP ancrés dans la stratégie de pêche et les performances de la pêcherie (chapitres 1 et 2).

b) Améliorer les connaissances sur l'écologie comportementale du thon dans le réseau de DCP ancrés des Maldives (chapitres 3 et 4).

Résumés des chapitres

Chapitre 1: Les Maldives - une nation de pêcheurs de thon

Ce chapitre décrit la pêche au thon aux Maldives et souligne son importance pour la population et le pays entier. Le chapitre est lié au premier objectif de la thèse. Il fournit des informations générales sur les Maldives et une perspective historique de la pêche au thon. Les Maldives sont un archipel de 1200 îles s'étendant sur 860 km du Nord au Sud. Les îles sont petites avec une superficie totale des terres de seulement 300 km². Plus de 80 % des îles sont situées à moins de 1 m au-dessus du niveau moyen de la mer et seules 33 îles ont une superficie supérieure à 1 km^2 (NBS, 2020). Il y a 187 îles habitées et 164 stations touristiques. Bien que le tourisme soit actuellement la principale source de revenus des Maldives, le nombre de Maldiviens employés dans ce secteur est plus faible que dans celui de la pêche.

Les pêcheurs des Maldives pêchent le thon de l'océan Indien depuis plus d'un millénaire. Les Maldiviens échangeaient des produits à base de thon avec d'autres pays étrangers avant 1153. Les pratiques durables des pêcheurs ont contribué à la poursuite de cette pêche au fil des générations. Sous les efforts déployés par le gouvernement et le secteur privé au cours des 50 dernières années, la pêche au thon est passée d'une pêche de subsistance traditionnelle à une pêche commerciale orientée vers l'exportation. Les navires de pêche au thon sont passés de petits voiliers en bois (~12 m) à de grands navires en fibre de verre (~30 m) équipés d'un moteur pouvant atteindre 600 chevaux. Le nombre moyen de marins travaillant sur un navire a également augmenté, passant de 10 à 25 pêcheurs sur les plus grands navires. Leur rayon d'action moyen a également augmenté, passant d'environ 24 km à 120 km, certains navires effectuant des voyages de plusieurs jours alors qu'ils ne faisaient auparavant que des excursions à la journée.

Les bateaux de pêche utilisent désormais des technologies modernes (par exemple, des jumelles, des radars à oiseaux, des détecteurs de poissons), ce qui facilite la pêche, mais augmente également les coûts opérationnels. Tous ces changements au cours des dernières décennies ont contribué à une augmentation significative des captures annuelles de thon aux Maldives. Les captures annuelles de thon sont passées de 33 000 tonnes en 1970 à 133 000 tonnes en 2019. Au cours des huit dernières années, les captures de thon sont restées supérieures à 100 000 tonnes. Plusieurs activités qui soutiennent cette pêche ont également évolué et comprennent la construction de bateaux, la réparation et l'entretien des moteurs, les entrepôts frigorifiques et les installations de transformation telles que les conserveries et les petites industries artisanales exploitées par les ménages dans les îles locales.

Bien que la pêche au thon contribue à environ 1,3 % du PIB national (NBS, 2014), elle constitue la principale source de revenus de plusieurs personnes vivant dans les îles extérieures. En 2019, l'exportation de produits marins qui comprennent principalement du thon (NBS, 2020) ont représenté plus de 150 millions USD pour le pays. Une grande partie du thon capturé est exportée vers la Thaïlande sous forme de thon congelé, tandis que la plupart des grandes longes de thon albacore capturées à la ligne à main sont exportées fraîches/réfrigérées vers l'Europe et les États-Unis. Près de 40% du thon capturé aux Maldives est consommé localement et on estime que la consommation de thon par habitant aux Maldives est supérieure à 100 kg/personne/an (FAO, 2016). La pêche au thon aux Maldives est désormais présentée comme un modèle pour d'autres États côtiers (Horne-Sparboth et al., 2015). La capture du thon "un par un", avec l'utilisation de l'hameçon et de la ligne, a permis d'assurer la sécurité alimentaire, d'offrir des opportunités d'emploi garantissant un revenu régulier aux pêcheurs et de distribuer les gains issus des ressources en thon à un plus grand nombre de familles au sein des communautés.

Les politiques du gouvernement des Maldives interdisant l'utilisation de filets à grande échelle pour la pêche au thon et empêchant les navires étrangers d'opérer à l'intérieur de la ZEE des Maldives ont contribué à garantir et à protéger la ressource et la pêche au thon locale. Pour œuvrer à la durabilité à long terme de la pêche, le pays s'est engagé auprès d'organisations internationales et développe des stratégies de gestion nationales. En 2019, dans le cadre d'une loi révisée sur la pêche, de nouveaux plans de gestion de la pêche ont été formulés et sont désormais mis en œuvre dans tout le pays. Des efforts sont également en cours pour améliorer la collecte de données de la pêche au thon par l'introduction d'applications qui pourraient aider les pêcheurs à transférer des informations sur leurs activités de pêche via une plateforme numérique. Diverses initiatives de recherche avec des collaborations internationales ont permis de mieux comprendre la pêche et des initiatives futures sont prévues pour élargir la capacité de recherche de l'Institut de recherche marine des Maldives (MMRI : Maldives Marine Research Institute).

Chapitre 2 : Les DCP ancrés aux Maldives

Ce chapitre décrit la pêche au thon à l'aide de Dispositif de Concentration de Poissons (DCP) ancrés aux Maldives et souligne son importance. Le chapitre traite du premier objectif de la thèse. Il fournit des informations générales sur le développement de la pêcherie sur DCP. Il décrit la construction et la méthode de déploiement des DCP. Enfin, le chapitre examine les approches de gestion adoptées par le gouvernement des Maldives pour assurer la durabilité de la pêcherie sur DCP.

Pour développer la pêche au thon dans les années 1970 et 1980, le gouvernement a pris plusieurs initiatives. L'une d'entre elles consistait à déployer des DCP expérimentaux, connus localement sous le nom de "oivaali kandhufathi". Cette expérience, soutenue par l'Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO), s'est avérée très fructueuse et a conduit au développement de la pêche sur DCP aux Maldives.

Un DCP ancré comporte quatre éléments fonctionnels : le flotteur ou bouée principale, les attracteurs - petit ensemble de flotteurs, l'ancre et la ligne d'amarrage (Shainee & Leira, 2011). Le flotteur actuel est une bouée rouge vif (environ 2 m de diamètre) construite avec une coque en fibre de verre et remplie de mousse. Un numéro de série unique pour chaque DCP et le nom du ministère responsable de la gestion du réseau de DCP sont gravés en relief sur la bouée. La ligne d'amarrage est conçue et importée de Corée du Sud. Les 100 premiers mètres de la ligne d'amarrage ont un cœur (ossature) en fer. L'ancre en béton et les fixations en acier inoxydable sont fabriquées aux Maldives. Tous les frais de construction, de déploiement et de maintenance des DCP (environ 15 000 USD par DCP) sont pris en charge par le gouvernement des Maldives.

Le déploiement est effectué à l'aide d'un bateau de pêche en fibre de verre. Deux grands blocs d'ancrage en béton sont installés de part et d'autre du navire sur la plate-forme arrière. Une extrémité de la corde est attachée à une chaîne qui est reliée aux blocs d'ancrage et l'autre extrémité de la corde est attachée au flotteur (bouée principale). Lors du déploiement, la bouée, attachée à la corde d'ancrage, est d'abord déployée en mer, puis les blocs d'ancrage reposant sur des rouleaux métalliques sont déployés. La corde conservée sur le pont du navire se déroule alors que l'ancre en béton coule au fond de la mer. Les petits flotteurs qui servent d'attracteurs sont également fixés à la bouée principale avant qu'elle ne soit déployée en mer.

Il existe plusieurs facteurs qui contribuent à la perte des DCP (Shainee & Leira, 2011). Les facteurs les plus courants sont : la dégradation causée par les poissons qui se nourrissent d'organismes fixés sur la ligne d'amarrage, la défaillance de l'attache due à la corrosion, l'usure des diverses pièces métalliques et l'implosion du flotteur (bouée principale) suite à une immersion prolongée. Bien que plusieurs DCP se détachent de la corde d'ancrage chaque année, les bouées sont souvent récupérées par les pêcheurs et renvoyées au ministère. Dans le passé, la récompense était de 65 USD (1000 MVR) pour la récupération et le transport de la bouée sur l'île habitée la plus proche. Depuis 2019, ce montant a été augmenté et la récompense est désormais de 325 USD (5000 MVR) pour la récupération d'une bouée. Le ministère a commencé à tenir des registres des bouées récupérées depuis 2016.

Les premières études de terrain menées par le Marine Research Centre (MRC, ancien MMRI) ont montré que les captures nationales de thon sont passées de 30 000 tonnes dans les années 1980 à 70 000 tonnes dans les années 1990. Les DCP, avec d’autres facteurs (e.g. modernisation des navires) ont contribué à cette augmentation. Aujourd'hui les informations sur les captures sont recueillies à l'aide d'un système de journal de bord par le ministère de la pêche. Les pêcheurs rendent compte de leurs activités de pêche, de leurs prises (y compris leurs prises accessoires) pour chaque sortie de pêche sur des feuilles de journal. À partir de ces informations et des données des observateurs, le ministère estime la quantité de thon capturée. On estime qu'environ un tiers de tous les thons capturés aux Maldives le sont autour des DCP (Miller et al. 2017).

L'utilisation des DCP a eu plusieurs effets positifs sur les communautés de pêcheurs. Elle a permis d'augmenter les revenus des pêcheurs en réduisant le temps de recherche des bancs de thon et donc la quantité de carburant dépensée. Elle a ainsi contribué à assurer la sécurité alimentaire de nombreuses communautés à travers les Maldives. Outre l'augmentation des captures de thon au niveau national, le réseau de DCP a contribué à soutenir la pêche au thon à la canne aux Maldives en garantissant des captures même les jours de mauvaise pêche en haute mer. Cette pêche sus DCP a permis de générer des revenus, notamment pour les communautés insulaires rurales, à la fois directement (pour ceux qui travaillent sur les navires de pêche) et indirectement (par le biais de diverses industries de transformation et d'autres entreprises liées à la pêche). Le principal défi auquel est confronté le gouvernement est le manque de connaissances scientifiques sur le rôle vraiment joué par les DCP sur les performances de la pêcherie, notamment à partir de connaissances sur la dynamique de l'agrégation des poissons et leur comportement dans le réseau de DCP. De telles informations pourraient aider à mieux gérer durablement la pêcherie sur DCP et notamment le nombre de DCP.

Chapitre 3 : Comportement du thon aux DCP ancrés déduit des connaissances écologiques locales (LEK) des pêcheurs de thon à la canne aux Maldives.

Ce chapitre est publié dans la revue PlosOne en tant qu'article évalué par des pairs. Ce chapitre étudie le comportement du thon aux Maldives sur la base des connaissances empiriques des pêcheurs. Il est lié au deuxième objectif de la thèse.

Dans cette étude, les connaissances écologiques locales (LEK) des pêcheurs ont été utilisées pour améliorer notre connaissance du comportement du thon, grâce à des entretiens personnels avec 54 pêcheurs à la canne provenant de différentes parties de l'archipel. Les résultats des entretiens suggèrent que pendant la mousson du nord-est, le thon est plus abondant sur le côté est des Maldives, tandis que pendant la mousson du sud-ouest, il est plus abondant sur le côté ouest des Maldives. La plupart des pêcheurs pensent que les thons ont tendance à rester associés aux DCP pendant 3 à 6 jours et restent à moins de 2 miles des DCP lorsqu'ils sont associés.

Les pêcheurs considèrent que les courants forts sont le principal facteur de départ des thons des DCP, bien que des températures élevées de la surface de la mer ou des conditions orageuses soient également considérées comme contribuant aux départs. Les courants modérés sont considérés comme une condition favorable à la formation d'agrégations autour des DCP, tandis que d'autres facteurs tels que la température de l’eau, la présence de proies et d’attractifs sur les DCP peuvent favoriser les agrégations. Les pêcheurs pensent également qu’une agrégation autour d'un DCP est composée de plusieurs bancs de thons, séparés par taille et par espèce. Les succès de capture seraient plus élevés à l'aube et en fin d'après-midi, lorsque les thons sont moins profonds dans la colonne d'eau.

Un résultat majeur de cette étude correspond à l'implication des pêcheurs locaux dans la science et par la suite dans la gestion de la pêche. Nous recommandons de mener régulièrement des études LEK (par exemple chaque année), plutôt que des études ponctuelles et éphémères, pour deux raisons principales. Premièrement, cela fournit un flux régulier d'informations permettant de générer des séries chronologiques à long terme qui sont utiles pour suivre les tendances de la pêche et de la ressource. Deuxièmement, cela permet aux pêcheurs de rester impliqués dans la science, en réalisant que leurs connaissances sont précieuses et utilisées par les scientifiques. Cela semble important pour combler le fossé entre les pêcheurs et les scientifiques, ce qui peut également contribuer à combler le fossé entre les pêcheurs et les gestionnaires.

Chapitre 4 : Une expérience *in situ* originale pour tester une hypothèse sur les mouvements des thons dans un réseau de DCP

L'objectif de ce chapitre (qui sera soumis à la revue Journal of Experimental Marine Biology and Ecology) est de tester une hypothèse sur une direction favorisée des mouvements de thons au sein du réseau de DCP ancrés. La première publication étudiant les mouvements de thons au sein du réseau de DCP aux Maldives à l'aide de la télémétrie acoustique (Govinden et al. 2013) a montré une absence de mouvements des thons marqués entre DCP voisins instrumentés, alors que dans toutes les autres études dans d'autres pays, des déplacements de thons entre DCP ont été observés (Dagorn et al. 2007, Robert et al. 2013, Rodriguez-Tress et al. 2017). Ils avaient pour cela instrumenté 8 DCP voisins, situés le long du bord Est de l'archipel des Maldives. Les auteurs avaient expliqué l'absence de mouvements entre DCP instrumentés par les grandes distances entre DCP (e.g. 2-14 km à Maurice et 7-31 km à Hawaii) alors que les distances pour Govinden et al. (2013) aux Maldives étaient comprises entre 38 et 60 km. Cependant, une autre hypothèse permettait également d'expliquer ce résultat : aux Maldives, les thons ont un mouvement général Ouest-Est ou Est-Ouest (vu que les DCP instrumentés dans Govinden et al. 2013 étaient tous alignés sur un axe Nord-Sud).

Afin de tester l'hypothèse d'une direction privilégiée dans les mouvements des thons dans le réseau de DCP ancrés des Maldives, et de mesurer le temps que les thons passent associés aux DCP aux Maldives, 65 listaos et 57 albacores ont été marqués avec des émetteurs acoustiques. Six évènements de marquage (thons marqués à un même DCP au même moment) ont été réalisés, répartis sur deux années (2017 et 2018) au sein d'une sous-section du réseau composée de 21 DCP équipés de récepteurs acoustiques. Seuls trois albacores (5,2% des albacores marqués) et un listao (1,5% des listaos marqués) ont été observés en train de se déplacer d'un DCP à l'autre. Il s'avère que ces quatre poissons ont été marqués ensemble au même DCP au cours du même évènement de marquage, au sein d'une cohorte de marquage composée de 11 listaos et 9 albacores. Ainsi, de tous les poissons marqués lors de cet évènement de marquage, 20% ont effectué des mouvements entre DCP, alors qu'aucun poisson marqué dans les cinq autres évènements de marquage ne s'est déplacé entre les DCP instrumentés. Bien qu'ils aient été marqués ensemble, les poissons qui se sont déplacés entre les DCP ont été détectés à différents DCP situés dans des directions différentes, ce qui suggère qu'ils n'avaient pas de préférence spécifique dans la direction de leur mouvement.

Si l'on combine tous les marquages acoustiques réalisés sur les albacores et les listaos autour des DCP aux Maldives (Govinden et al. 2013 et cette étude), pour 9 des 10 évènements de marquage, aucun thon marqué n'a visité un autre DCP, même lorsque les thons ont été marqués sur un DCP entouré d'autres DCP dans plusieurs directions. L'ensemble de ces résultats suggère qu'il n'y a pas de direction privilégiée des thons lorsqu'ils se déplacent au sein du réseau de DCP ancrés, mais que la quasi absence de mouvements entre DCP s'explique par les distances importantes entre les DCP aux Maldives. Chaque DCP au sein du réseau des Maldives semble ainsi agir comme un DCP individuel, par opposition à un réseau de DCP où les DCP seraient connectés, avec des thons pouvant visiter plusieurs DCP.

Ainsi, les DCP aux Maldives, avec de grandes distances inter-DCP, semblent avoir peu d'effet sur la rétention des thons au sein du réseau tout en restant un outil utile pour les pêcheurs pour accéder aux thons et les capturer. Au-delà de l'intérêt pour les Maldives, les résultats de cette étude fournissent également des connaissances utiles pour les plans de gestion des DCP dans d'autres pays ou les plans de gestion des DCP dérivants (flottes de senneurs) avec l'objectif de maintenir le rôle des DCP en tant qu'outils de pêche tout en minimisant les effets possibles sur le comportement de mouvement du thon, ce qui pourrait éventuellement affecter négativement la biologie du thon comme suggéré par certaines études avec l'hypothèse du piège écologique (Hallier & Gaertner 2008 ; Dagorn et al. 2013).

Discussion générale et conclusion

Bien que le secteur du tourisme constitue la principale source de revenus du pays (la contribution au PIB en 2019 était de 66 %), il génère environ 4 fois plus d'emplois (NBS, 2020) en comptant toute la filière liée à la pêche, soit environ 25% de la population Maldivienne. C'est donc un secteur majeur de ce pays et sa durabilité, ou son développement, sont au cœur des préoccupations.

Les Maldives ont une ZEE d'environ 900 000 kilomètres carrés. Près de 85 % des activités de pêche au thon ont lieu près des atolls, dans un rayon de 200 000 kilomètres carrés. Par conséquent, environ 80 % de la ZEE des Maldives est à peine utilisée pour la pêche. Les pratiques des pêcheurs, avec un rayon d'action relativement faible, font donc que près de 80% de la ZEE des Maldives agissent comme une Aire Marine Protégée (AMP), sans qu'elle soit officiellement créée. Ce simple constat pourrait inciter une extension spatiale des zones de pêche de certains grands navires Maldiviens, voire de concevoir des bateaux plus adaptés à des marées plus longues, mais les impacts écologiques, sociaux et économiques d'un tel développement devront également être pris en compte avant de développer une telle initiative. Une meilleure compréhension de la pêche maldivienne est évidemment utile et nécessaire pour aider le gouvernement à établir ses mesures de gestion de la pêche, mais aussi la CTOI dans le cadre général de l'océan Indien. Il est important de souligner que ces études sur la pêche maldivienne, qui dépend des DCP ancrés, ont également un intérêt beaucoup plus large au niveau mondial. À l'échelle mondiale, peu de pêcheries à la canne ont été fructueuses et peuvent encore opérer ; elles ont presque toutes disparu. L'apport significatif des DCP dans la performance des canneurs Maldiviens (assurant ainsi environ 1/3 de leurs captures) joue certainement un rôle dans la durabilité de cette pêcherie, et la densité particulièrement faible des DCP semble limiter très fortement tout impact négatif potentiel sur l'écologie des poissons. En ce sens, la pêcherie des Maldives sous DCP ancrés, quasiment unique dans le monde de la pêche à la canne, peut être considérée comme une référence et doit faire l'objet d'efforts de recherches pour l'accompagner dans ses objectifs de durabilité.

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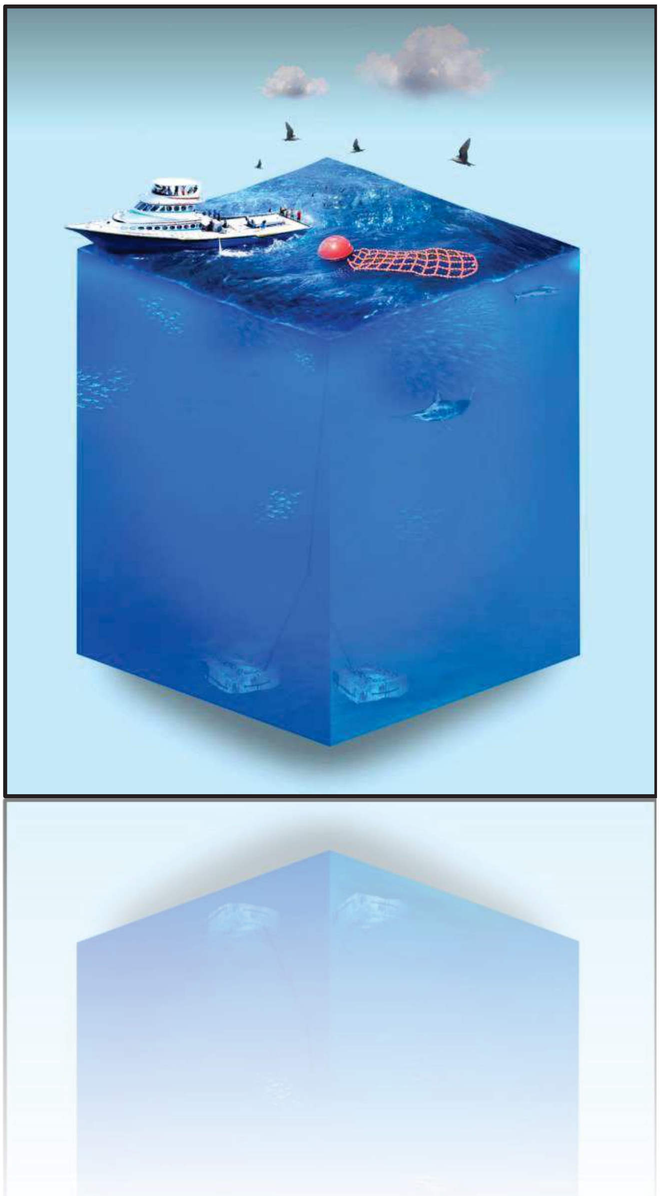


General Introduction

Global fish production (including crustaceans and molluscs) has increased and has reached about 179 million tons in 2018 at an estimated value of nearly USD 4 billion (FAO, 2020). Three main groups dominate fish trade in terms of its value – finfish (66%), crustaceans and molluscs (22%) and other invertebrates (12%) (FAO, 2020). Major marine finfish species catches have increased over the years (Figure 0.1). In 2018, anchoveta dominated the catches with 7.0 million tons, followed by alaska pollock with 3.4 million tons and skipjack tuna with 3.2 million tons (FAO, 2020). A large portion (~86%,156 million tons) was for human consumption thus providing a significant contribution to global food security. Since 1961 the average fish consumption rate has increased by 3.1% per year. The per capita food fish consumption also rose on average by about 1.5% every year from 9.0 kg in 1961 to 20.5 kg by 2018 (FAO, 2020).

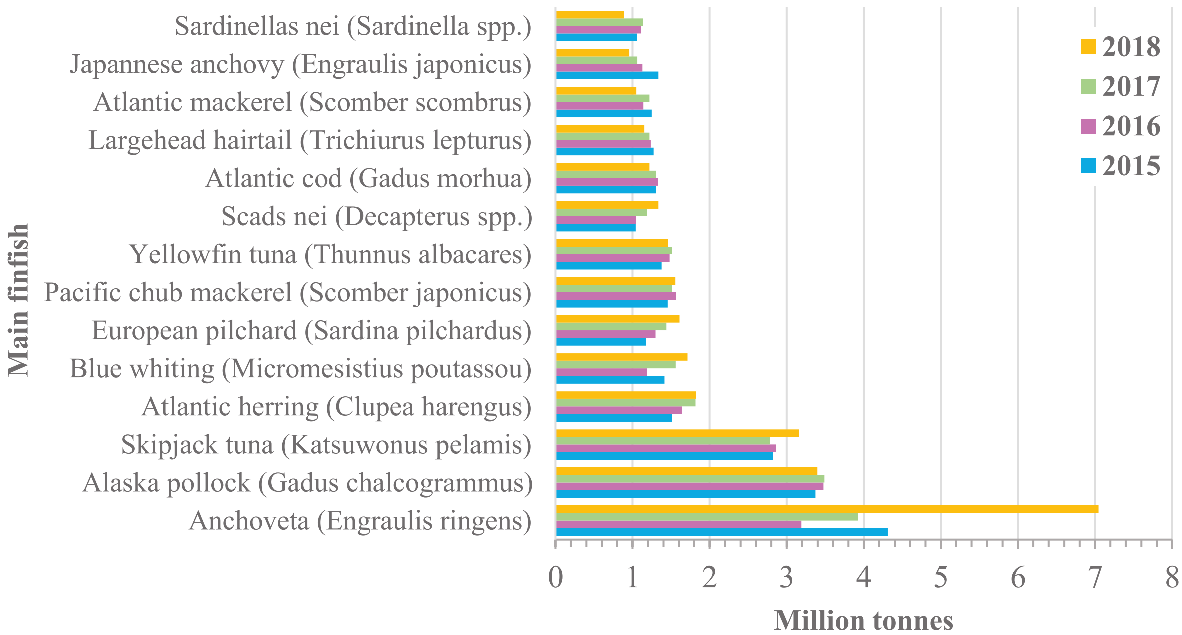


Figure 0.1: Global catches of main finfish species from 2015 to 2018 (Data source: FAO, State of the World Fisheries and Aquaculture, 2020).

With 7.9 million tons, catches of tuna and tuna-like species also reached its highest levels in 2018 (SOFIA, 2020). Due to high catches, economic value and international trade, seven species of tuna are considered as greater importance – skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), bigeye tuna (*Thunnus obesus*), albacore (*Thunnus alalunga*), Atlantic bluefin tuna (*Thunnus thynnus*), Southern bluefin tuna (*Thunnus maccoyii*) and Pacific bluefin tuna (*Thunnus orientalis*). Global tuna catches have continually increased over the years. The average catch comparison between 2015 and 2019 of the most significant five groups of tuna (Figure 0.2) showed that 86% of the catch is from skipjack and yellowfin tuna. Nearly 66% of the global tuna catch is landed by purse seiners (Figure 0.2).

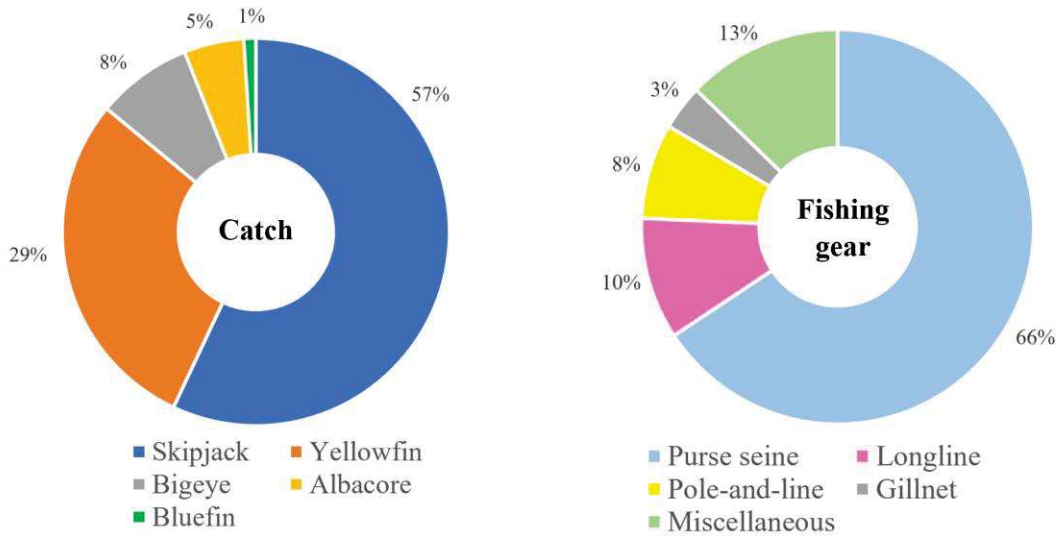


Figure 0.2: Average proportion of the global tuna catches and the gear used for harvesting the catches between 2015 and 2019 (Source: ISSF, 2021)

The industrial fisheries started to expand in the 1940s and 1950s to cater to the demands of canneries. Initially the longline fishery expanded to the high seas in the 1950s followed by the purse seiners in the 1960s and 1970s. By mid 1970s the Japanese, Republic of Korea and Taiwan started conducting longline operations all over the world. The development of super-cold storage facilities on board the longline vessels shifted their target species from yellowfin and albacore tuna to bigeye tuna for the *shashimi* market. In the 1960s Spanish, French and Japanese bait boats started their operations in the Atlantic off West Africa. As the purse seine fishery developed and expanded, the pole and line fishing in different parts of the world started to decrease. The efficiency of the purse seine fishery increased with the use of modern technology such as bird radars and helicopters.

In the Indian Ocean, tuna catches have increased steadily since the 1980s with the arrival of tropical tuna purse seiners. This ocean hosts the second largest tuna fishery in the world (FAO, 2020) with 21% of global tuna catches (ISSF, 2021). Although there are several species of tuna in the Indian Ocean, four major species mostly contribute to the total Indian Ocean tuna catches – yellowfin tuna (YFT), skipjack tuna (SKJ), bigeye tuna (BET) and albacore tuna (ALB). Their catches reached a peak in 2005 with 1.2 million tons (Figure 0.3). In 2019 there was an 8% decline in catches of these four species from their 2018 catch. Both skipjack and yellowfin tuna contributed to about 88% of the catches in the Indian Ocean. Purse seine is the leading fishing gear (42.8% of the total catches) (Figure 0.4) (IOTC, 2020).

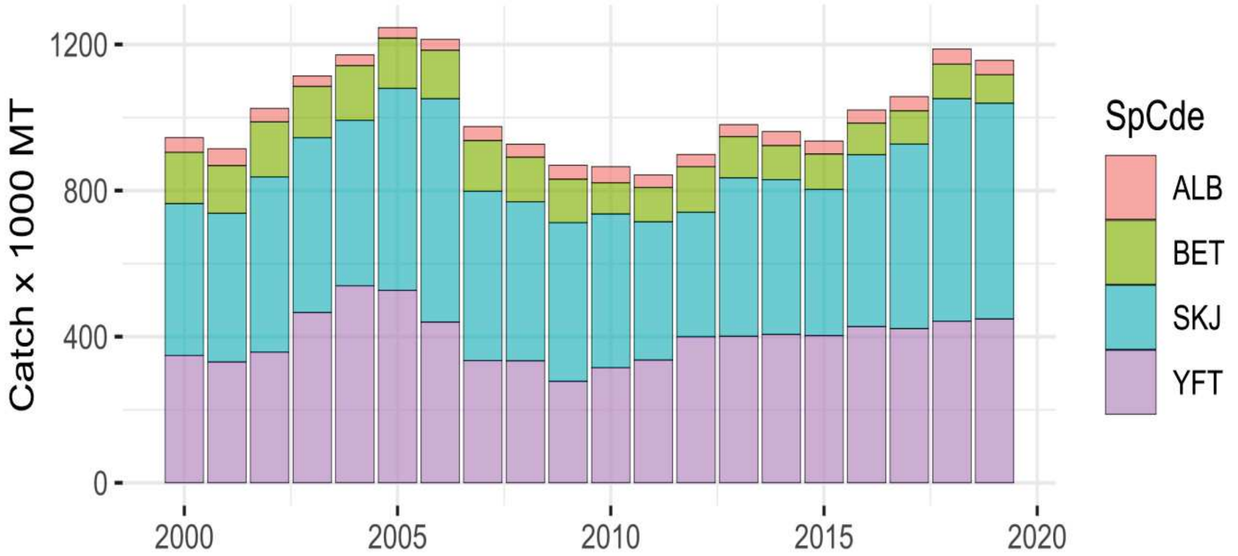


Figure 0.3: Catches of the four main species of tuna (skipjack tuna (SKJ), yellowfin tuna (YFT), bigeye tuna (BET) and albacore tuna (ALB) in the Indian Ocean (Source: IOTC-2021-WPTT23(DP)-DATA03-NC.xlsx).

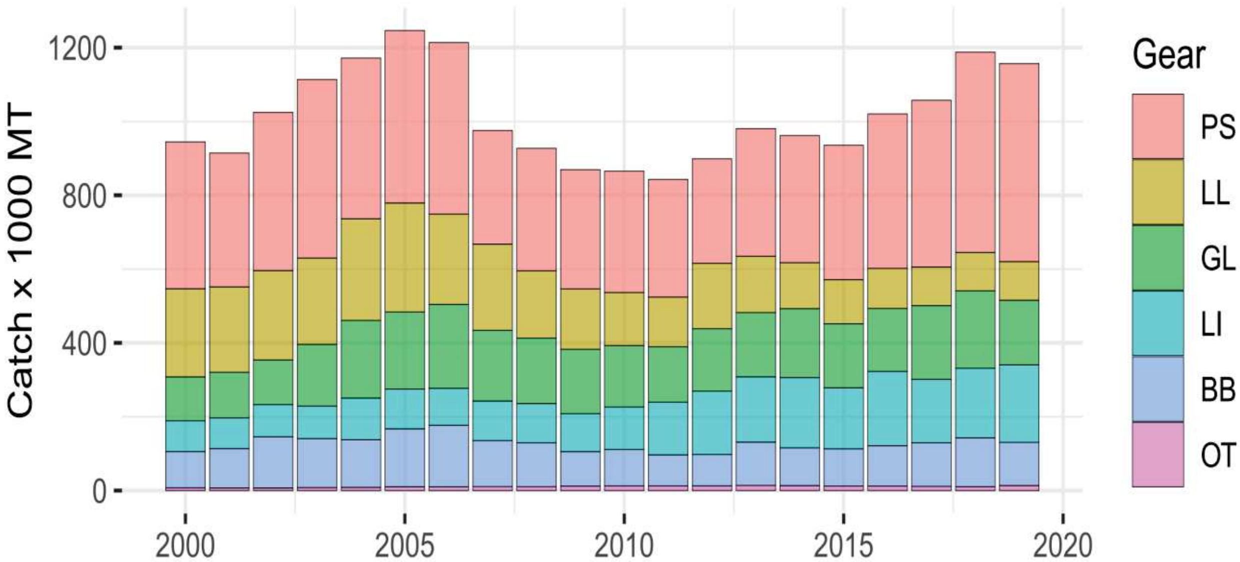


Figure 0.4: Catches of the four main tuna species by fishing gear in the Indian Ocean. (PS – purse seine, LL – longline, GL – gill net, LI – line, BB – bait boat, OT – other) (Source: IOTC-2021-WPTT23(DP)-DATA03-NC.xlsx).

Several coastal countries (Figure 0.5) have been fishing tropical tuna (mainly skipjack, yellowfin and bigeye tuna) near their coasts for centuries. The Maldivian fishers, for instance, have been catching tuna in the Indian Ocean for over a millennium (MMRB 2, 1996). Before the industrial fleet started fishing in the Indian Ocean, the Maldives were one of the leading nations in catching tuna in the Indian Ocean (Figure 0.6). Today Maldivian fishers in their bait boats using pole and line gear harvest about 20% of the total Indian Ocean tuna catches (Figure 0.7), making the Maldives the 3rd largest fishing country in the Indian Ocean behind Europe and Indonesia (Figure 0.7).

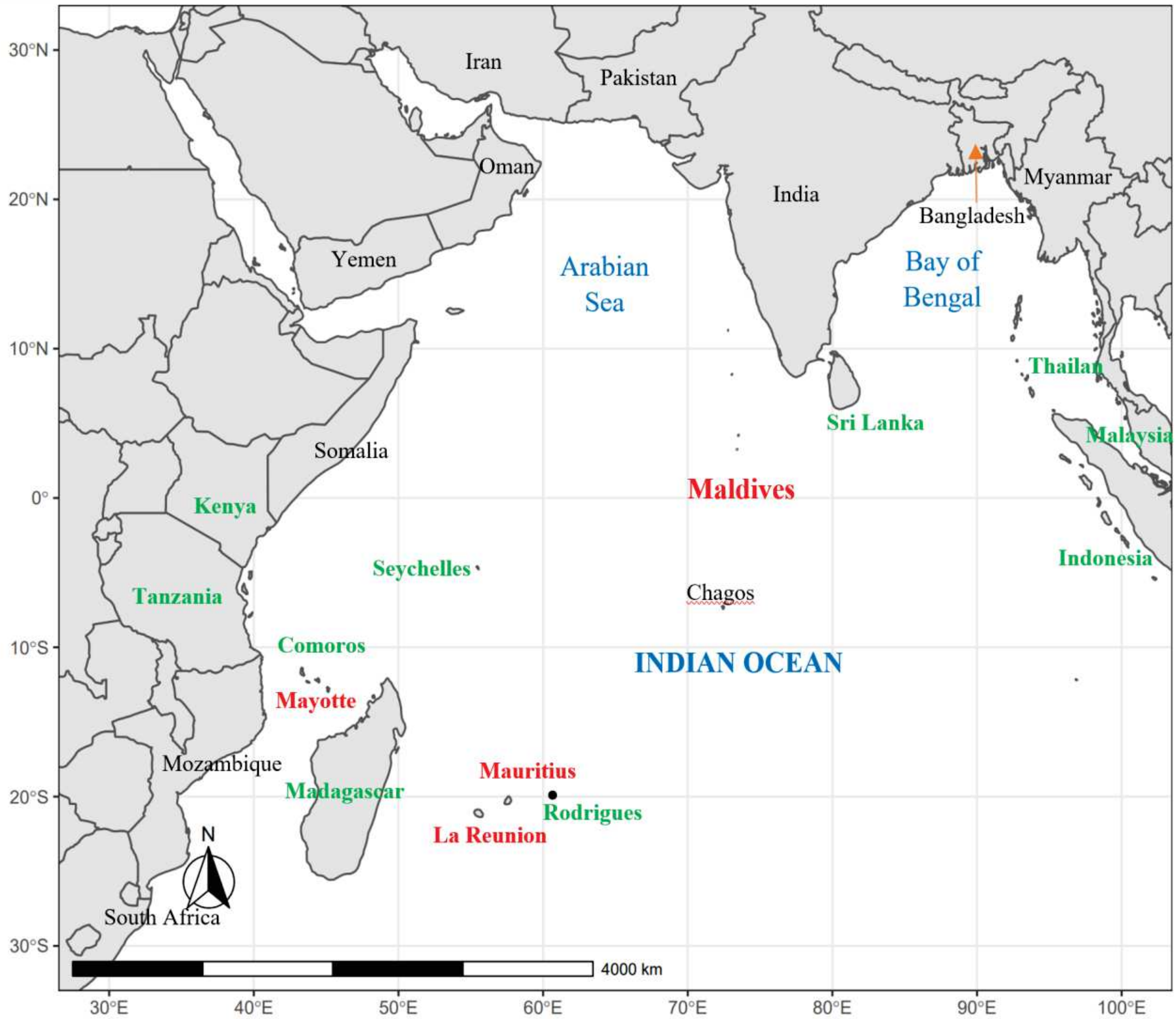


Figure 0.5: Coastal countries in the Indian Ocean. (Countries that have AFADs managed by the government are labelled in red; Countries that have used or use AFADs for fishing in the Indian Ocean without a continuous FAD policy by the government are labelled in green).

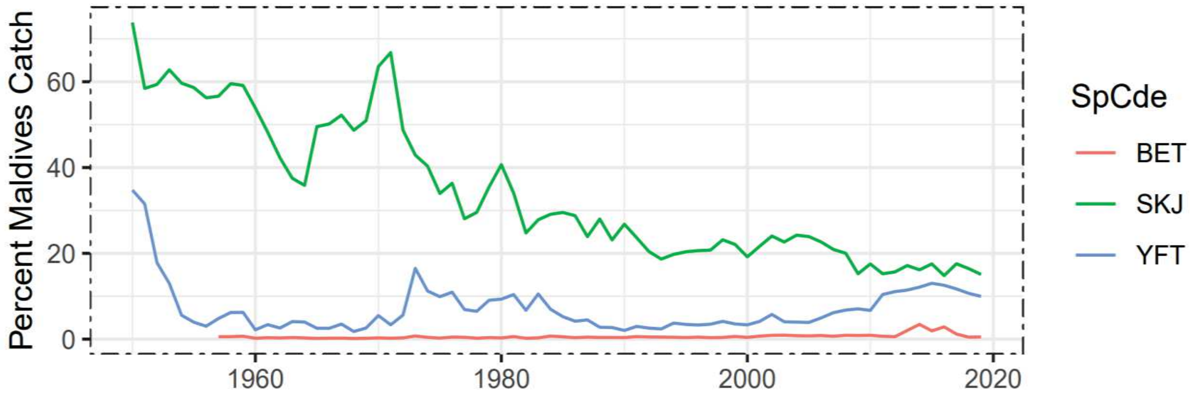


Figure 0.6: Maldives tuna catches as a percentage of the total Indian Ocean catch for skipjack tuna (SKJ), yellowfin tuna (YFT) and bigeye tuna (BET) (Source: http://iotc.org/WPTT/22AS/DATA/03-NC.xlsx).

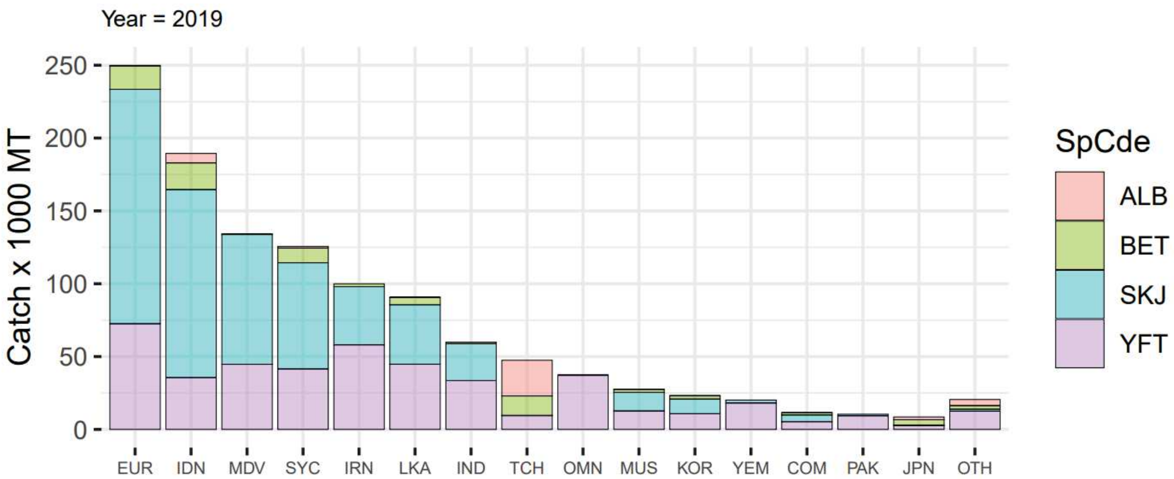


Figure 0.7: Four main species of tuna caught (skipjack tuna (SKJ), yellowfin tuna (YFT), bigeye tuna (BET) and albacore tuna (ALB) by different fleets in the Indian Ocean in 2019 (Source: IOTC-2021-WPTT23(DP)-DATA03-NC.xlsx).

As the fishing activities expanded with rise in demand for tuna, the catch also increased. With the expansion of the industrial tuna fishery in the Indian Ocean the need for management of tuna stocks became more evident and realized. Thus, a regional fisheries management organisation (RFMO) known as the Indian Ocean Tuna Commission (IOTC) was formed in 1996. The IOTC is responsible for the regional management of tuna and tuna-like fisheries resources. The objective of IOTC is “to promote cooperation amongst contracting members to ensure through appropriate management, the sustainable use of fishery resources”. Both tropical and temperate tunas are targeted in the Indian Ocean.

The fleets operating in the Indian Ocean range from artisanal to large scale industrial vessels. Since tuna are highly migratory and many countries exploit shared stocks, cooperation among all parties fishing in the Indian Ocean is essential to ensure the sustainability and the good health of tuna stocks as well as their ecosystems. There are currently 32 members (including almost all coastal countries – Figure 0.5) in the IOTC who are either engaged in harvesting or in transhipments and fishing agreements. The Maldives also realizing the importance of managing regional tuna stocks became a full member of the IOTC in 2011. Since then, it has engaged actively in meeting the standards set for the fishery by the organization and to provide information that could enhance the management of the tuna stocks as well. It has undertaken several research endeavours on behalf of the IOTC such as the tagging activities to study the migration of tuna in the Indian Ocean. Maldives has been instrumental in promoting the interests of other coastal states too.

There are several species of tuna and mackerel managed by the IOTC. These include:

1. Skipjack tuna (*Katsuwonus pelamis*)
2. Yellowfin tuna (*Thunnus albacares*)
3. Bigeye tuna (*Thunnus obesus*)
4. Albacore (*Thunnus alalunga*)
5. Frigate tuna (*Auxis thazard*)
6. Kawakawa (*Euthynnus affinis*)
7. Longtail tuna (*Thunnus tonggol*)
8. Indo-Pacific king mackerel (*Scomberomorus guttatus*)
9. Narrow-barred Spanish mackerel (*Scomberomorus commerson*)

Of these, skipjack, yellowfin and bigeye tuna form the bulk of the catch (Figure 1.3). Skipjack tuna (Figure 0.8) is the smallest species of the major commercial tuna species (FL 40 to 80 cm) with a maturity at 43 cm and lifespan 6 to 10 years (ISSF, 2021). Yellowfin tuna (Figure 1.8) size typically range between 40 and 170 cm (FL) reaching a maturity at 85 to 108 cm (FL) and a lifespan of 8 years (ISSF, 2021). Bigeye tuna (Figure 1.8) has the longest lifespan of the three species – 15 years, reaches maturity between 102 and 135 cm (FL) with a common length of 40 to 180 cm similar to yellowfin tuna (ISSF, 2021).

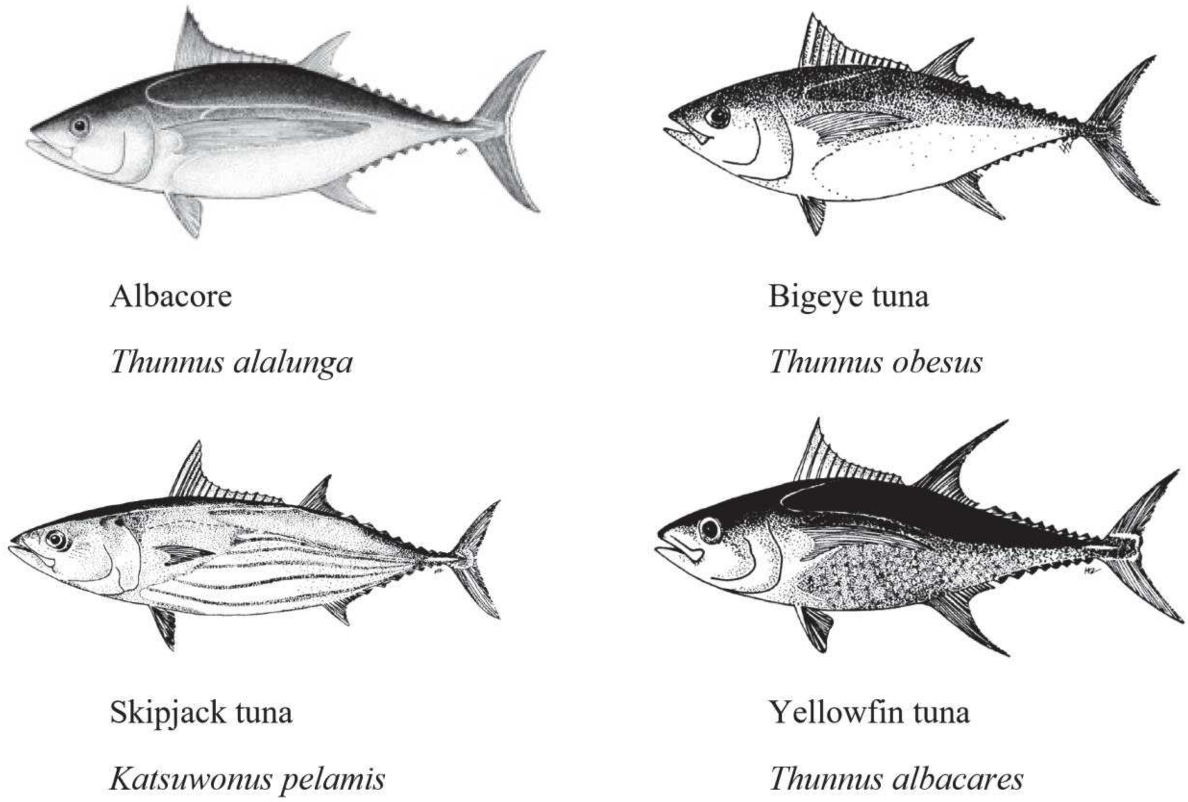


Figure 0.8: Commercially significant tuna species caught from the Indian Ocean (Source: FAO & MRC).

Several species of fish including tuna are known to be associated with large floating objects (Castro, Santiago, & Santana-ortega, 2002). Some of these aggregations occur around natural objects such as flotsam (Riera et al., 1999), logs (Greenblatt, 1979) algae (Michael J Kingsford, 1992, 1995; Safran & Omari, 1990) and jellyfish (Broduer, 1998; Manseuti, 1963). Artificial structures that are fixed or drifting in the ocean are known to attract fish too. These include rafts (Heyerdahl, 1950), fish cages in coastal waters (Boyra, Sanchez-jerez, Tuya, Espino, & Haroun, 2004; Tim Dempster, Sanchez-jerez, Bayle-sempere, Giménez-casalduero, & Valle, 2002), and many other structures like oil platforms found in the open sea (Franks, 2000). Based on this experience for several decades fishers have been building and deploying Fish Aggregation Devices (FADs) to attract and help catch tuna (Girard, Benhamou, & Dagorn, 2004).

Several hypotheses have been proposed to explain the attraction of pelagic fish like tuna to floating objects. These include: (1) shelter from predators (Gooding & Magnuson, 1967), (2) use as cleaning stations (Gooding & Magnuson, 1967), (3) spatial reference (Klima & Wickham, 1971), (4) comfortability stipulation (Batalyants, 1992), (5) concentration of food supply (Kojima, 1956) (6) schooling companion (Hunter & Mitchell, 1967), (7) substitute environment (Hunter & Mitchell, 1967), (8) indicator-log (Hall, 1992), and (9) meeting point (Fréon & Misund, 1999). It is also suggested that the association of several fish species to drifting objects can be for protection against predators (Castro et al., 2002; Mitchell & Hunter, 1970), to increase possibility for feeding and to increase chances in arriving at suitable habitats for settlement (M. J. Kingsford & Choat, 1986).

The two most popular hypotheses that could explain the associative behaviour of tuna with drifting objects are the 'indicator-log' hypothesis (Hall, 1992) and the 'meeting point' hypothesis (Freon & Dagorn, 2000). According to the indicator log hypothesis, naturally floating objects are commonly found in frontal zones, caused by oceanic convergences, and fish that associate with these floating objects will be positioned in these productive areas (Freon & Dagorn, 2000; Hall, 1992). According to the meeting point hypothesis, tuna associate to floating objects to increase their chances of encountering isolated individuals or other smaller aggregations and schools that allow formation of larger schools thus increasing the survival of the species (Freon & Dagorn, 2000).

Modern technology has helped fishers increase their efficiency over the years. Such technological devices helped fishers land bigger catches with less effort and less expenses. One such device is the modern fish aggregation device (FAD). There are two types of FADs used by tuna fishers. Drifting fish aggregating devices (DFADs) and anchored fish aggregating devices (AFADs) both attract tropical tunas and other pelagic species. These FADs are used worldwide by fishers using different fishing gears to increase the catchability of tropical tunas. Strategies of long-distance fleets using DFADs and those of small- or medium-scale fleets using AFADs differ, due to the range of the vessels, and the nature of the FADs. Large purse seiners use DFADs (often equipped with echosounder buoys) at the scale of an oceanic basin and their strategy is clearly to find tuna moving in the ocean. Drifting FADs help them find areas with high local abundance of tuna, and once in a fishing zone, FADs make tuna easier to find and catch. Small-scale or medium-scale fisheries of coastal countries use AFADs along the coast. Like long-distance fleets, local fishers also use FADs to make tuna more accessible and vulnerable to fishing, but the difference is that the main fishing zone is fixed: their national waters often close to the coast. Contrarily to long-distance fleets, these small- or medium-scale fleets do not track tuna in the ocean but exploit them when they pass through their coastal waters.

Nearly 40% of the world tuna caught in tropical oceans are fished around floating objects (L Dagorn, Holland, Restrepo, & Moreno, 2013). Due to its efficiency the use of FADs has expanded in both artisanal and commercial fisheries across the world (Fonteneau, Pallarés, & Pianet, 2000; Freon & Dagorn, 2000). Since the 1990s, thousands of FADs have been deployed in the oceans across the world resulting in modification of the surface habitat of the pelagic ecosystems, due to increasing the number of floating objects (Baske, Gibbon, Benn, & Nickson, 2012; L Dagorn et al., 2013; Dupaix et al., 2021; Maufroy et al., 2017). This change has increased scientists' concern on the possible impacts of FADs on the ecology of tuna (L Dagorn et al., 2013; Hallier & Gaertner, 2008; Marsac, Fonteneau, & Ménard, 2000a). Some believe that the FADs in the ocean could act as ecological traps (Battin, 2004; Schaefer & Fuller, 2002) and alter the migration of tuna (Marsac, Fonteneau, & Ménard, 2000b) with potential negative consequences on their biology. At any one time there are nearly 50,000 to 100,000 FADs in the ocean (Baske et al., 2012).

In the Indian Ocean AFADs are used in many countries. In some countries such as the Philippines and Indonesia, arrays consist of several hundreds of AFADs, while in others (e.g. the Maldives, Mauritius, Comoros, La Réunion), arrays are composed of a few tens of AFADs. AFAD arrays are either funded and maintained by national governments (e.g. Maldives, La Réunion, Mauritius), or deployed by private companies, with no government coordination (e.g. Indonesia). When a government decides to fund an anchored FAD array, the objective is clearly to ensure food security and support its local tuna fishery, by facilitating the access to tunas. This could be done by reducing the search cost and/or increasing catches. One could also consider that FAD arrays could benefit to local fisheries by keeping fish longer in the area as tuna would "bounce" between FADs. More FADs could then also help increase the total time fish spend associated to FADs, making them more accessible to fishing (Pérez et al., 2020). On the other hand, too many FADs could question the sustainability of the fishery on the long term, similar to DFADs and their possible ecological impacts.

When setting a FAD array, the number of FADs, as well as the distances between them, represent key questions, as they could have direct impacts in terms of fishing strategies, catches, as well as relationships between fishers. In terms of tuna behaviour, the number of FADs could have direct effects on their movements (see Pérez et al., 2020). When FADs are closer to each other tuna tend to visit more FADs and stay associated with FADs longer (Pérez et al., 2020). The total biomass of fish associated to FADs also depends on the local fish population but also on the FAD density (Capello et al., 2016). Consequently, the number of

FADs is likely to play a role on the proportion of fish that is not associated to floating objects, e.g. in free-swimming schools. As fishers usually exploit tuna in different types of schools, the relative numbers of these types of schools also plays a role in the fishing strategy, e.g. the distribution of the fishing effort among the different school types.

Thesis objectives

Although it is believed that the tuna fishery in the Maldives has existed for over a millennium (MMRB 2, 1996) and similarly the practice of fishing on drifting logs, the AFAD fishery started in the early 1980s (Naeem & Latheefa, 1994a). Initial trials proved that the catch increased from 30,000 tons in 1980s to 70,000 tons in 1990s (Naeem, 1988). Today the tuna catches in the Maldives are above 100,000 tons per year and the fishery provides direct employment to more than 17,500 fishers (Ministry of Fisheries, Marine Resources and Agriculture: MoFMRA, 2019). About one third of tuna caught by Maldivian tuna fishers are caught around 55 AFADs (Miller, Nadheeh, Jauharee, Anderson, & Adam, 2017) deployed across the country spreading 800 km. The choice by the Maldivian government for a low-density AFAD array could appear quite unique in a world where the standards are more towards large numbers of AFAD. There are no privately owned AFADs in the Maldives. The Maldivian government takes the responsibility of constructing, deploying and looking after the AFAD array. All pole and line tuna fishers have equal access to all the AFADs and information on the position of the AFADs (coordinates) are publicly shared on the MoFMRA website: https://www.gov.mv/en/organisations/ministry-of-fisheries-marine-resources-and-agriculture.

The aim of this research is to improve our knowledge on the fisheries ecology of tuna within the Maldives AFAD array in order to better understand the drivers of the sustainability of the Maldivian pole and line fishery. Our approach is to use different scientific techniques (e.g. electronic tagging, local ecological knowledge) to collect data to be analyzed in the framework of the sustainability of the fishery. Two specific objectives structured the work:

- To review and understand the role of AFADs in the fishing strategy and performance of the Maldivian pole and line fishery (chapters 1 and 2)
- To improve our knowledge on the behavior of tuna in the Maldivian AFAD array (chapters 3 and 4).

Thesis layout

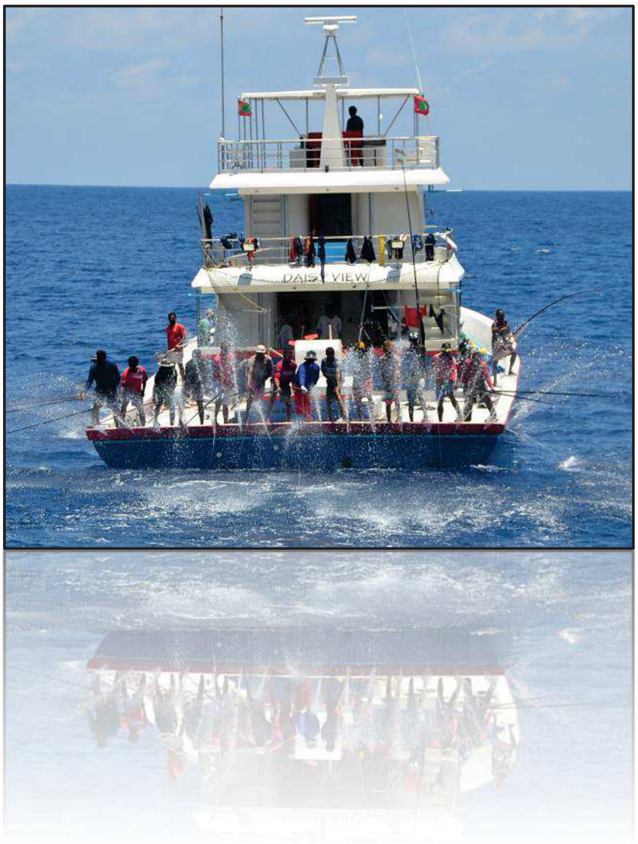
This thesis contains four main chapters and a general discussion. The first chapter (Maldives: a tuna fishing nation) describes the tuna fishery in the Maldives. It details the evolution of the fishery that moved from a traditional pole and line fishery (until the 1970's) to a more modern commercial tuna fishery that lands more than 100 000 tons of tuna a year. The chapter highlights the efforts made by the government and the private sector to transform the fishery.

The second chapter (Anchored FAD fishery in the Maldives) describes the development and use of anchored fish aggregating devices (AFADs) in the tuna fishery of the Maldives. It highlights the development, design, installation, and fishing operation that takes place at the AFADs. The management strategies adopted by the government is also emphasized.

The third chapter (Tuna behaviour at anchored FADs inferred from Local Ecological Knowledge (LEK) of pole and line tuna fishers in the Maldives) investigates the behavior of tuna within the Maldivian AFAD array from fishers empirical knowledge. The chapter looks at seasonal variations in abundance of tuna around AFADs in the Maldives and characteristics of the associative behaviour of tuna with AFADs. The information used in this chapter was obtained through personal interviews of experience tuna fishers who are at present actively engaged in fishing.

The fourth chapter (An original in situ experiment to test a hypothesis on tuna movements within a FAD array) corresponds to an experiment conducted to test a scientific hypothesis, following results from a first study on tuna behavior at AFADs in the Maldives using electronic tagging (Govinden et al., 2013). The objective was to test the hypothesis that tuna in the Maldives adopt a general east-west or west-east movement, including the possible role of the inter-FAD distances. In addition to this hypothesis test, the chapter estimates the durations of individuals' association with FADs, with the aim of comparing them with the durations measured in the Maldives previously (Govinden et al., 2013) and also in other FAD arrays with lower inter-FAD distances. More than 100 tuna were tagged with acoustic transmitters and were released at four AFADs for this study within an array of 21 instrumented AFADs.

The general discussion examines how the results obtained in this thesis can help recommendations for management of AFAD fishery in the Maldives. Future research areas are also highlighted.



Chapter 1

The Maldives: a tuna fishing nation

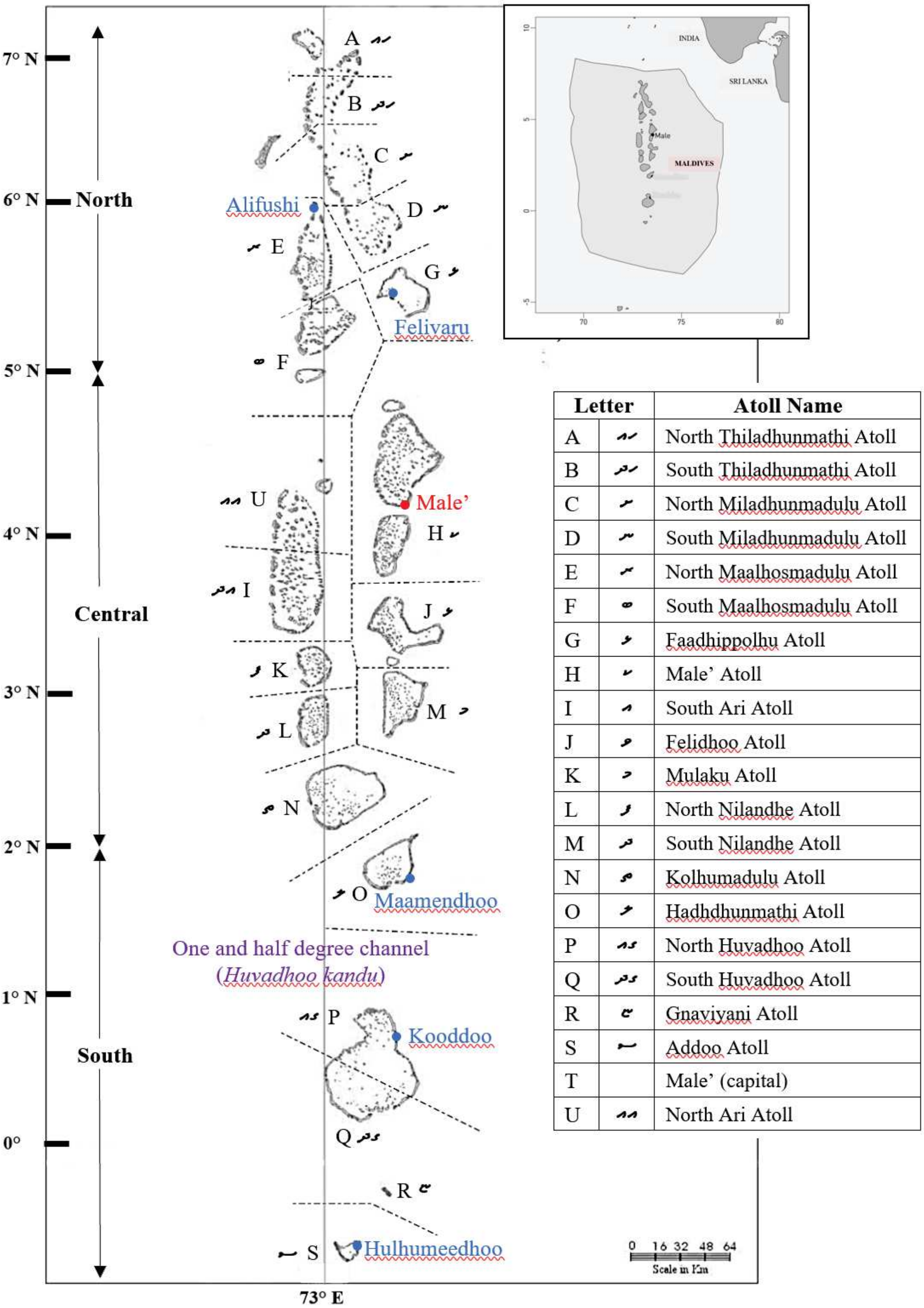
1 Introduction

1.1 The Maldives

The Republic of Maldives is a small island nation lying southwest of India and Sri Lanka, in the central Indian Ocean. It comprises of a chain of 26 natural atolls located on the Laccadive-Chargos submarine ridge between 7.1°N, 1°S and 72.5°E, 73.3°E. This chain is 860 km long and contains 1200 coral islands spread over 90, 000 km^2. From 6.0°N to about 2.5ºN, the Maldives atolls are arranged in a double chain, whereas south of 2.5°N the atolls form a single chain (Figure 1.1) and are separated with wide deep channels through which migratory fish such as tuna pass from one side to the other. The islands are small and the total land area of the entire country is only about 300 km^2. Over 80% of the islands are less than 1 m above mean sea level while only 33 islands are more than 1 km^2 (Maldives National Beaureau of Statistics: NBS, 2020). Some islands are inhabited (187) while some others are used as tourist resorts (164) and industrial islands (28) such as those assigned for fisheries related activities: Felivaru, Maandhoo and Kooddoo. Few islands are designated as protected islands due to environmental significance.

The Maldives islands are grouped into 20 administrative atoll units (Figure 1.1) with Malé' as its capital. Each administrative atoll is assigned an English / Dhivehi letter and a unique name as well (Figure 1.1). Several important coastal ecosystems are associated with the islands in the Maldives. These include coral reefs, seagrass beds, mangroves, lagoons and beaches. The total reef area including the lagoons is 21, 372 km^2 (Naseer & Hatcher, 2004). The Republic of Maldives is the seventh largest coral reef system in the world and has two of the largest natural atolls in the world: Bodu Thiladhummathi Atoll (A, B, C, D: 3,789 km^2) and Huvadhu Atoll (P, Q: 3, 278 km^2) (Figure 1.1) (Naseer & Hatcher, 2004). Maldives has a rich coral reef ecosystem with 1200 different fish species (Anderson, 2005b).

The depth of the sea inside the atolls vary from 25 m to 75 m, where Huvadhoo atoll (P, Q) is the deepest. Neritic tuna species such as kawakawa and frigate tuna are frequently caught using troll lines inside the atolls. Huvadhoo atoll (Figure 1.1: P and Q) is the only atoll within which skipjack and yellowfin tuna are frequently caught inside the atoll. There are several seamounts in the south of Maldives. The Sathoraha seamount is the most famous and most utilized by the fishermen. It is in the one and half degree channel between Laamu (O) and north Huvadhoo atoll (P). This seamount attracts several species of tuna of varying sizes and plenty of sharks.



Letter		Atoll Name
A	ހއ	North Thiladhunmathi Atoll
B	ހދ	South Thiladhunmathi Atoll
C	ށ	North Miladhunmadulu Atoll
D	ނ	South Miladhunmadulu Atoll
E	ރ	North Maalhosmadulu Atoll
F	ބ	South Maalhosmadulu Atoll
G	ޅ	Faadhippolhu Atoll
H	ކ	Male' Atoll
I	އ	South Ari Atoll
J	ވ	Felidhoo Atoll
K	މ	Mulaku Atoll
L	ފ	North Nilandhe Atoll
M	ދ	South Nilandhe Atoll
N	ތ	Kolhumadulu Atoll
O	ލ	Hadhdhunmathi Atoll
P	ގއ	North Huvadhoo Atoll
Q	ގދ	South Huvadhoo Atoll
R	ޏ	Gnaviyani Atoll
S	ސ	Addoo Atoll
T		Male' (capital)
U	އއ	North Ari Atoll

Figure 1.1: The Maldives islands are grouped into 20 administrative atolls. Each atoll has a unique name, an atoll capital and a letter assigned to it. Male' is the capital of the Maldives.

The Maldives EEZ adjoins India and Sri Lanka in the north and the British Indian Ocean Territory (Chagos) in the south. The total area of the EEZ is about 895 thousand square kilometers. Outside the atolls the waters quickly plunge to several hundred meters and tuna is abundant in these clear oceanic waters. Maldives experience two monsoons. The southwest monsoon (May to October) is wet with strong winds, plenty of storms and periods of heavy rain. The northeast monsoon (December to March) is dry with calm seas. During the southwest monsoon period, the wind and current is from the southwest and west. These winds can be very strong, making it impossible for fishers to head out to sea during some weeks. In the south of the Maldives, the effect of the monsoon-related currents is weaker and is influenced by the equatorial system (Anderson, 2005a).

There are a total of 568,362 people living in the Maldives (NBS, 2021) recorded in 2020 census, and about 1/3 of these are foreign migrant workers. Nearly a third of the total population is concentrated around the capital, Malé. Apart from Malé region, the most populated areas include North Thiladhunmathi, Huvadhoo Atoll and Addoo Atoll. About 48% of the Maldivian population are women and unemployment rate is below 10%. The literacy level across the Maldives is very high (98.3%) (NBS, 2014).

1.2 Tuna fishing: a key national activity

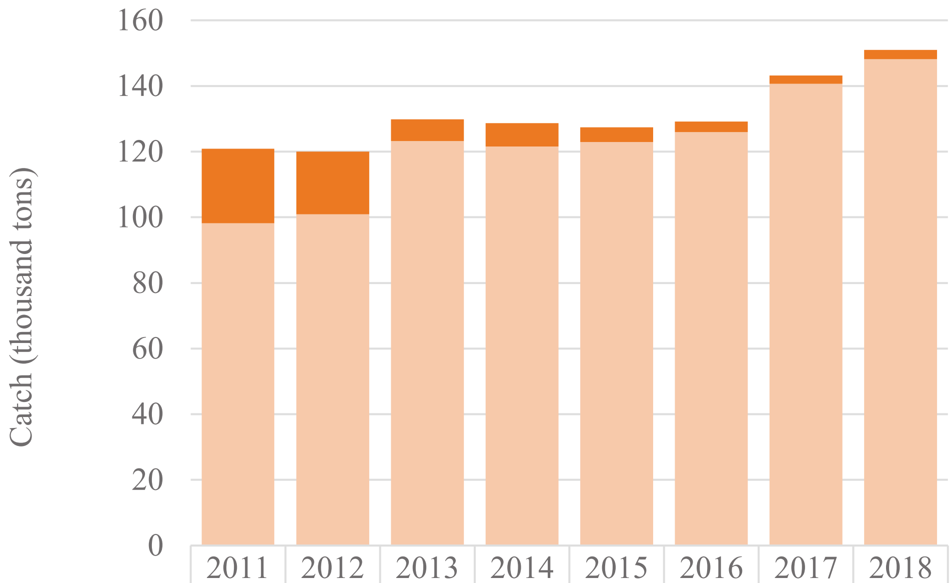
Although tourism is the main source of income for the Maldives, the number of locals employed in this sector is lower than in the fisheries. Fishing in the Maldives have continued to be of significance importance to the Maldivians over several centuries. Tuna fishing was considered an important activity even before Maldives conversion to Islam in 1153-1154AD (Lister, 2016). Thus, it is believed that people living in these atolls have caught and consumed tuna for over a millennium (MRS 1996). In 1327, the Arab traveler Ibn Battuta described the process of making dry fish (cooked, smoked dried tuna). In his accounts of his visits to the Maldives in 1343-44, he described the importance of tuna for the Maldivians (Gray 1889; Gibb 1929). He further stated that the dried tuna was exported to China, India and Yemen. A Chinese Official, Ma Huan who was in the Maldives in 1425 stated that travelers used dried tuna on their voyages (Yang, 2019). It is believed that dried tuna produced in the Maldives was an important source of protein for the sailors and travellers in the Indian Ocean (Yadav, Abdulla, Bertz, & Mawyer, 2020). The voyages of Francois Pyrard de Laval in early 1602 also gave a vivid account of the tuna fishing activities in the Maldives (Gray, Bell, & Eds, 2010). Pyrard's account described the use of dried fish to pay tax by the locals to the king (Gray et al., 2010).

He also described that the tuna fishery had high yield and was the main source of employment for the island communities. Bell, 1882 also described the process of making dry tuna which can be preserved for several months.

Although there were only limited references, it was clear that 'dried fish' trade (most likely skipjack) was expanding rapidly in the south Asia region (Yadav et al., 2020). By the eighteenth century, this product had become a popular commodity in Sri Lanka and was called 'Maldive fish'(Hockley, 1935). In the nineteenth century, it was mainly Bohra merchants (Indian traders) that carried fish from Maldives to Sri Lanka in their sailing vessels (Bell, 1882). Dried tuna was popular among the Maldivians as it can be stored for a long period (> a year) without refrigeration thus making it available throughout the year. Even today the method of fishing and drying of tuna has remained similar to what was reported by Ibn Battuta in the fourteenth century (Yadav et al., 2020).

Nowadays, large quantities of tuna are caught and consumed across the Maldives (Figure 1.2). A major transition in the fishery began in the 1970s and 1980s with mechanization of the vessels and introduction of new processing techniques (Shiham, Anderson, & Hafiz, 2003). In addition to tuna, Maldivian fishers harvest several other pelagic and reef resources. These include:

1. Billfish – sailfish and marlin
2. Wahoo
3. Dolphin fish
4. Several types of reef-based food fish – snappers, emperors, jacks, groupers
5. Ornamental fish
6. Sea cucumber



	2011	2012	2013	2014	2015	2016	2017	2018
Other Species	22.6	19.1	6.6	7.1	4.4	3.2	2.5	2.8
Tuna	98.2	100.9	123.2	121.5	122.9	126.0	140.7	148.2

Figure 1.2: Total catches of tuna and other marine species harvested in the Maldives between 2011 to 2018 in thousand tons. (Source: NBS, 2020).

In the past, with limited educational opportunities, as well as limited transport and communication between the islands and the international communities, the percentage of the population engaged in fishing was much higher across all the atolls (Figure 1.3). With the expansion of education, tourism and other economic opportunities, the tendency towards 'white collar' jobs became more popular among the youth. This led to a decline in the number of youth joining the fishing industry. To encourage youth to join the fisheries sector several efforts have been made.

a) The modern fishing vessels are more convenient to work on with proper accommodation, toilet facilities and with modern navigation and fishing equipment.
b) The flexibility for fishers in taking leave to attend family responsibilities.
c) Opptunity to work on vessels that operated from their own island enabled the fishers to spend more time with family.
d) With higher prices paid by the companies for the fish (from MVR 5.00 (USD 0.35) to MVR 20.00/16.00 (USD 1.33/1.03) per kg of tuna) the income for the fishers also became more attractive.
e) Fishing is no longer seen as a low level job among communities.

During the COVID-19 pandemics, when the country went into a shutdown and there was zero tourist arrival, many locals who were working in the tourist resorts became unemployed. These locals had to return to their communities and several of them chose to join the tuna fishery. Thus, the tuna fishery helped them earn an income to sustain their families even during the pandemics, highlighting the importance of the tuna fishery, as an alternative source of income, for the nation.

1.3 Industries linked to tuna fisheries

Currently, there are nearly 1000 fishing vessels of varying sizes (length: 12 to 35 m) employing more than 17,500 fishers (MoFMRA, 2020) who go out fishing on these vessels regularly. In addition, several other industries such as boat construction, tuna processing factories, ice making plants, engine repair and maintenance workshops are linked to the tuna fishery (Figure 1.4) which provides employment opportunities for thousands. In fact, the fisheries industry employs nearly half the working population in the outer islands (further away from the capital Male') of the Maldives. Apart from these small businesses, there are also several other service providers such as those that transport and supply fuel for the operation of the vessels and companies that process and preserve the fish.

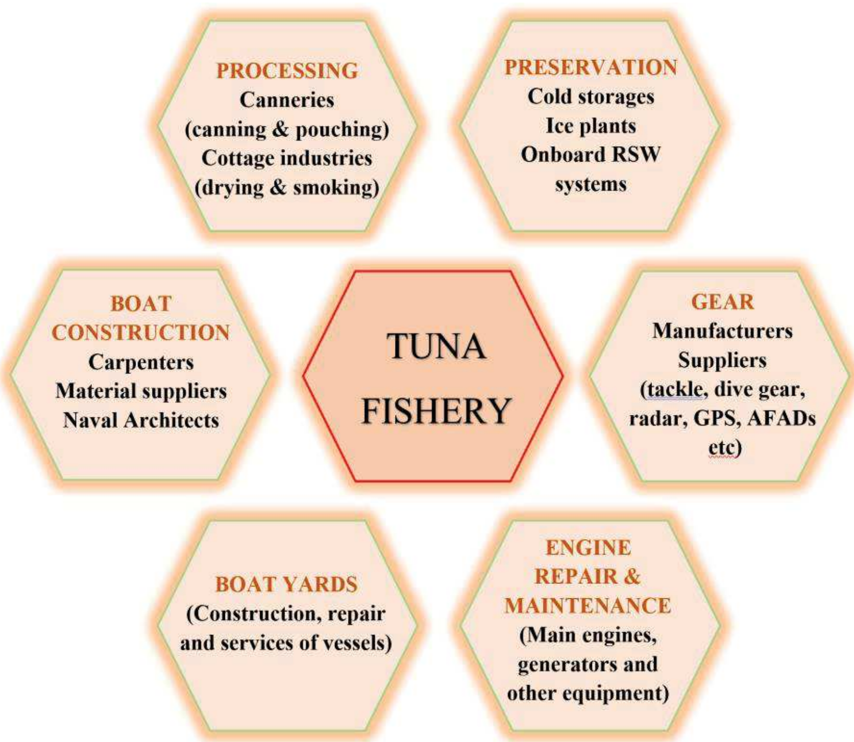


Figure 1.3: Industries directly and indirectly linked to the tuna fishery across the Maldives.

1.4 Fish consumption and trade

Tuna is extremely popular and widely consumed throughout the Maldives. It is estimated that Maldivians consume more than 100 kg of tuna per person per year (FAO, 2016). Most Maldivians prefer fresh skipjack tuna over yellowfin tuna. This is often due to the strong smell given out by yellowfin tuna during the preparation of the local dish *garudhiya*. Other species of tuna such as frigate tuna and kawakawa are also consumed throughout the country but they can be purchased at a cheaper price than skipjack and yellowfin. Tuna is a cheap source of protein readily available for the locals. One kilogram of fresh tuna (skipjack and yellowfin) in the local markets could range from USD 0.5 to 3.0 depending on the supply. Other sources of protein include imported meat such as chicken and beef. In 2019, about 42,000 tons of fish were consumed in the Maldives (Figure 1.5 / MoFMRA, 2020).

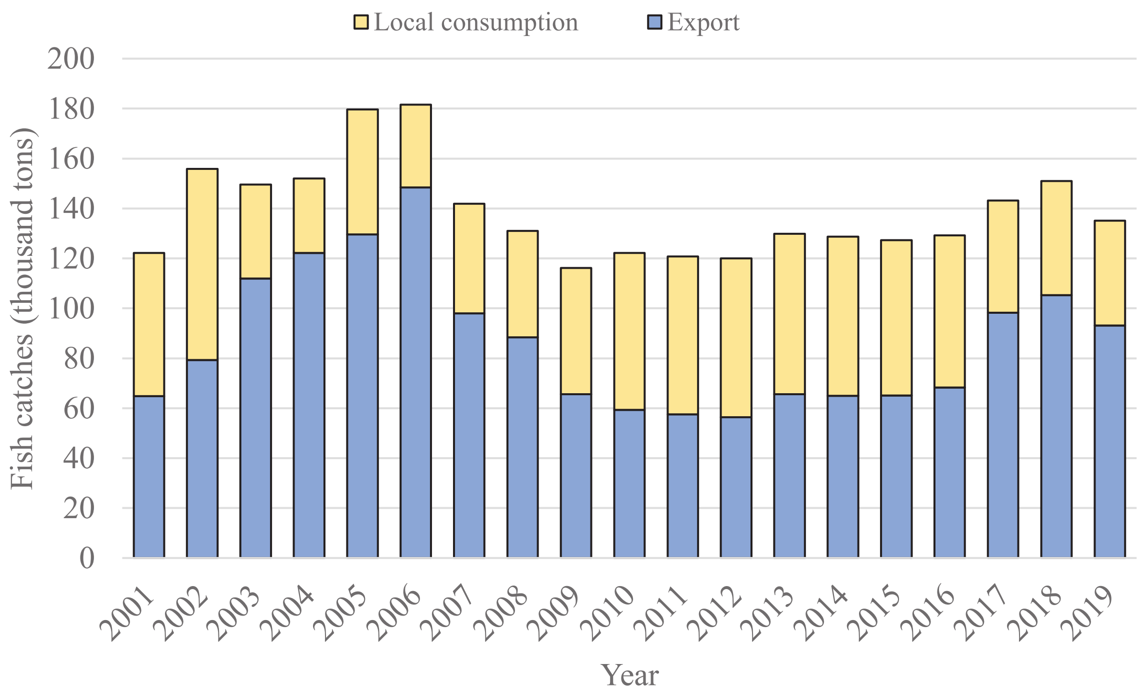


Figure 1.4: Fish catches consumed and exported from the Maldives between 2001 and 2019 (Source: NBS, 2020).

Tuna is also the main export from the Maldives. There are historical records indicating that Maldives exported dried tuna to Yemen, India, Sri Lanka, Myanmar and Indonesia from the fourteenth to the nineteenth century (Yadav et al., 2020). The main market for dried tuna or 'Maldive fish' was Sri Lanka. In 1971 this market collapsed and the government of the Maldives had to find other avenues to obtain foreign-exchange through the sale of fish products. Several agreements were signed with Japan, Spain and Thailand to send their vessels to purchase fish from Maldivian fishers (Ali, 2007). This initiated a change in the characteristics of the tuna fisheries from a solely domestic fishery harvesting for local consumption to a commercial fishery where tuna is caught for export purposes (Hohne Sparborth, Adam, & Ziyad, 2015).

Although the tuna fishery contributes to about 1.3% to the national GDP (NBS, 2014), it is the main source of income for several people living in the outer islands. In 2019, Maldives earned more than USD 150 million from the export of marine products which mainly comprises of tuna (NBS, 2020). A large portion of the tuna caught is exported to Thailand as frozen tuna, while most large yellowfin loins as fresh/chilled tuna is exported to Europe and USA.

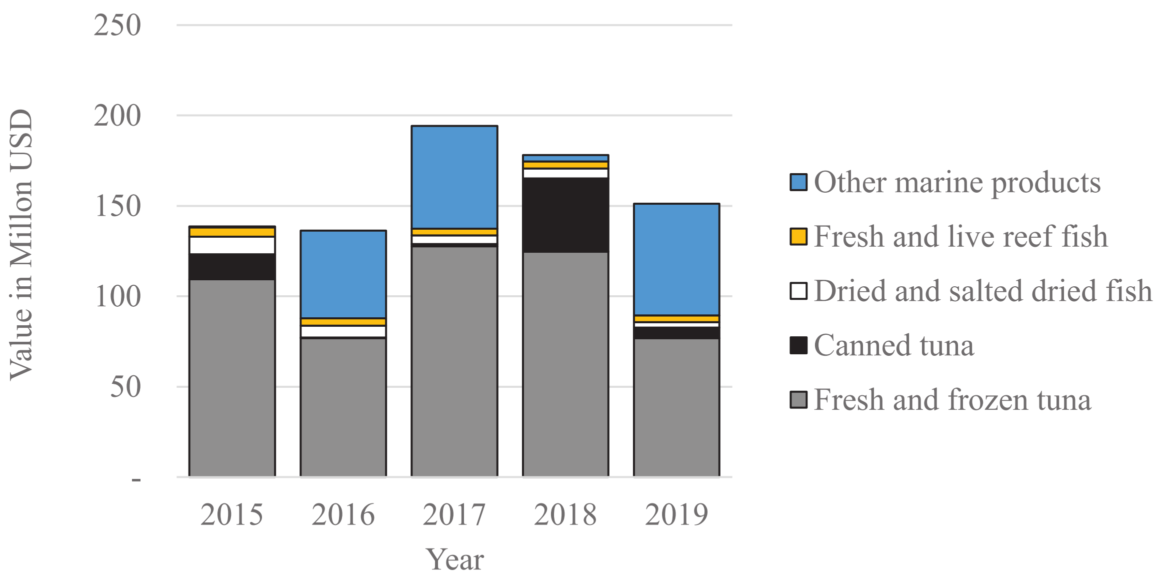


Figure 1.5: Economic value (in million USD) of marine products exported from the Maldives between 2015 and 2019 (Source: NBS, 2020).

2 Tuna fisheries

2.1 From a traditional to a modern fishery

Traditionally, tuna was mainly caught by pole and line method using livebait from wooden boats built on local islands (Figure 1.6). The vessels were powered by sail and oars. They operated close to their islands up to 35 km (Gray et al., 2010). The traditional pole and line gear consists of a strong wooden stick attached to which was a thick cotton cord. At the other end of the cord was a barbless hook (Gray et al., 2010). White silvery bait collected from the reef were chummed to attract tuna to the vessels followed by angling (Gray et al., 2010). Prior to 1974 the tuna fishers had to totally depend on wind to go out fishing as the whole fishing fleet was comprised of sailing vessels. As a result, they could not venture very far from their home port and the vessels had to be small (~ 10 to 12 m) so that they could still come back to a shelter within the atolls using oars even if the wind died down. Laborious tasks, such as bailing excess water from the vessel, maintaining the circulation in the bait tank and splashing of water during angling, were all carried out manually.

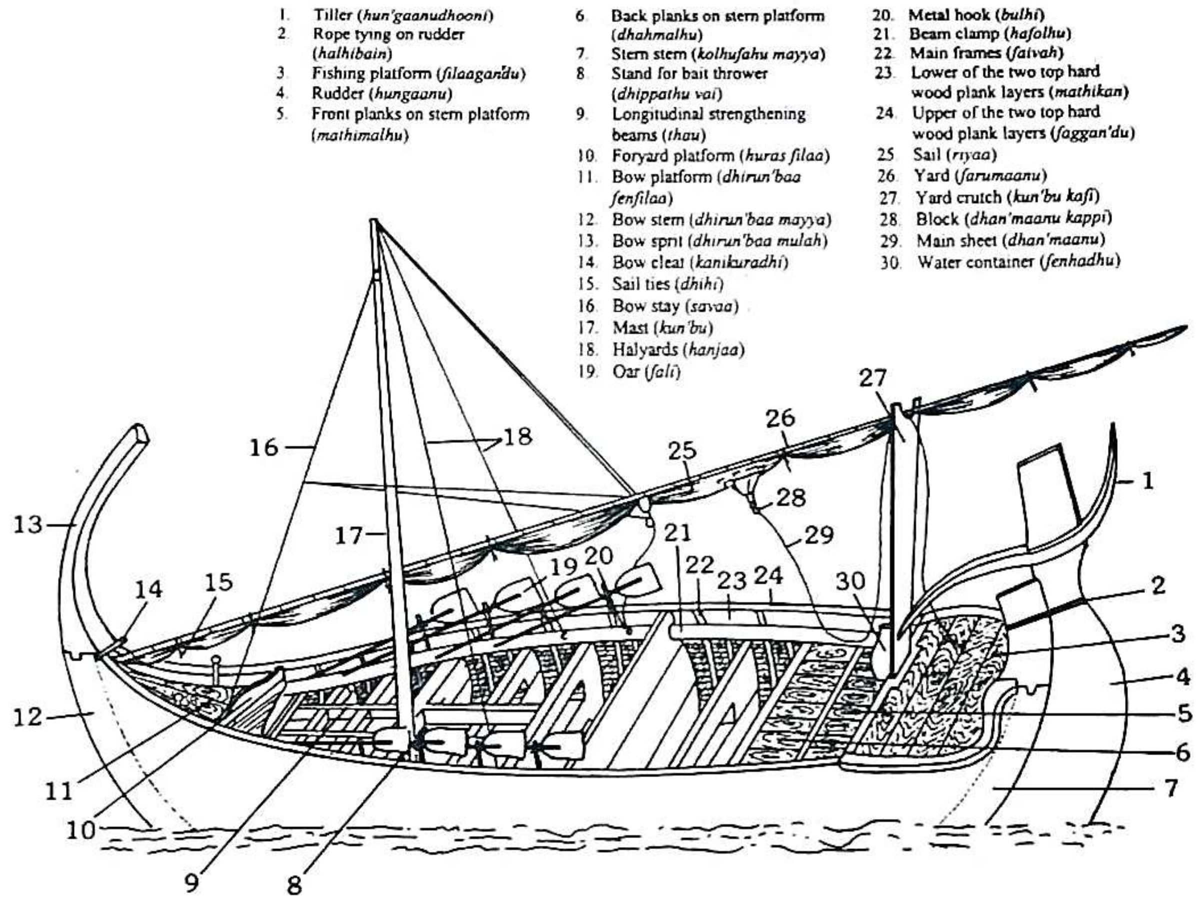


Figure 1.6: Traditional sailing *masdhoani,* pole and line fishing vessel (extracted from Jauharee and Chamberlain, 1997).

Mechanization was the solution to overcome this hindrance while making the fishers more versatile. To mechanize the vessels the government sought assistance from the Japanese government. In September 1974 work began to modify and install an engine on a sailing vessel named 'Ummeedh'. This was completed and the vessels was launched on 10th December 1974. At the beginning fishers were apprehensive to mount engines on their sailing vessels as many believed that the tuna schools would disperse with the noise generated from the engines. Once the fishers started realizing the benefits of mechanization and the increase in catch by mechanized fishing vessels, the fishers' desire to install engines on their sailing vessels increased. According to the data gathered by MOFA, sailing vessels could conduct on average 100 daily fishing trips in a year while mechanized vessels were able to fish for 200 days. In addition, a mechanized vessel caught 3 to 4 times more fish than a sailing vessel in a year. Other advantages that fishers attained due to mechanization included the use of water pumps that helped them keep the tuna catch fresh, improve circulation of water in the bait tanks, use mechanicals sprayers during angling and reach the ports faster to sell their catch while the fish is still in good condition.

From 1975 to November 1977 more than 400 sailing vessels were fitted with Yanmar 22 hp and 30 hp engines. These engines were particularly selected based on their cost, easiness in installing them on existing sailing vessels and the after-sale services available. The engines were provided to the fishers on a long-term loan basis for about MVR 35000.00 (USD 2270.00). In addition to the Japanese assistance, the United Kingdom provided 50 engines of type Lister 25W. By the end of the project in 1998, the Maldivian government has assisted in deploying engines on 1648 vessels. In addition, customs import duty was exempted for those engines imported by private fishing vessel owners.

Before the 1970s, the livebait used for tuna fishing was caught using relatively simple methods. Since there were no face-masks available for observing the movement of bait fish under water, fishers poured coconut oil on the surface to improve through-water visibility. Scraped fish fillets were used to attract livebait and to concentrate them in an area. Bait fishing was done during the daytime, usually first thing in the morning just before heading out to catch tuna (Anderson, Waheed, & Adam, 1998). Only hand-made cotton nets were available, so baiting was difficult because the nets required constant repairs. The beginning of tourism in the early '70s helped open the country to the outside world, enabling the Maldives to interact with fisheries experts from other countries and to import various products easily from abroad. Easy access to the international markets helped fishers to obtain better fishing gears such as bamboo poles, nylon nets, monofilament lines and barbless hooks. Access to facemasks also helped fishers to be more efficient in catching livebait.

The Maldivian fishing vessels (locally known as *masdhoani*) (Figure 1.7) are constructed on local islands inside a temporary shed called *odi haruge*. Until the 1970s, local woods such as coconut were used for building the hulls. Since the expansion of the fishery, a gradual shift from locally available wood to imported wood took place, but the local design of the hull was still maintained. The real change in design of the fishing vessels began with the initiation of the Maldives Fish Wealth Exploitation Project (MFWEP) which focused on constructing better fishing vessels and to provide these vessels to fishers under an affordable scheme. To this purpose, a government-owned boatyard was established in Raa Atoll, Alifushi and the construction of vessels began in January 1983. This initiative was an important milestone in modernizing the tuna fishery in the Maldives.

Figure 1.7: Traditional mechanized *masdhoani*.

In the past, many communities were poor and could not afford a fishing vessel. Thanks to this project, several communities across the Maldives were able to commence tuna fishing activities. This project also led to the change in design of the traditional fishing vessel to the more modern fishing vessel that fishers use today. The newly designed wooden vessels were called 2nd generation fishing vessels (Figure 1.8). Further changes were later brought to improve the design of the vessels, resulting in 2nd generation mark 2 and mark 3 vessels. The first one hundred 40-feet long vessels constructed under this project were distributed to fishers in the southern most four atolls to encourage the improvement of fisheries in the southern atolls.

Figure 1.8: Second generation masdhoani. Specially designed wooden boat for pole and line fishing. There was not shelter.

Figure 1.9: Small shelters were built on second generation style masdhoani to store gear, fishers' belongings and food.

As new designs were introduced, several modifications were made by local carpenters and fishers in different communities to the wooden fishing vessels. Some started building small shelters on the vessels (Figure 1.9), initially to store various things used on the vessel. By 2002, large (18 m) fibreglass boats with proper shelter, toilets and kitchen were introduced in the fishery. These vessels had larger bait tanks and fish holds making it possible for the fishers to spend several days out at sea fishing. Modern vessels are about 30 m in length (Figure 1.10).

Figure 1.10: Present – modern fiberglass masdhoani widely used for tuna fishing across the Maldives.

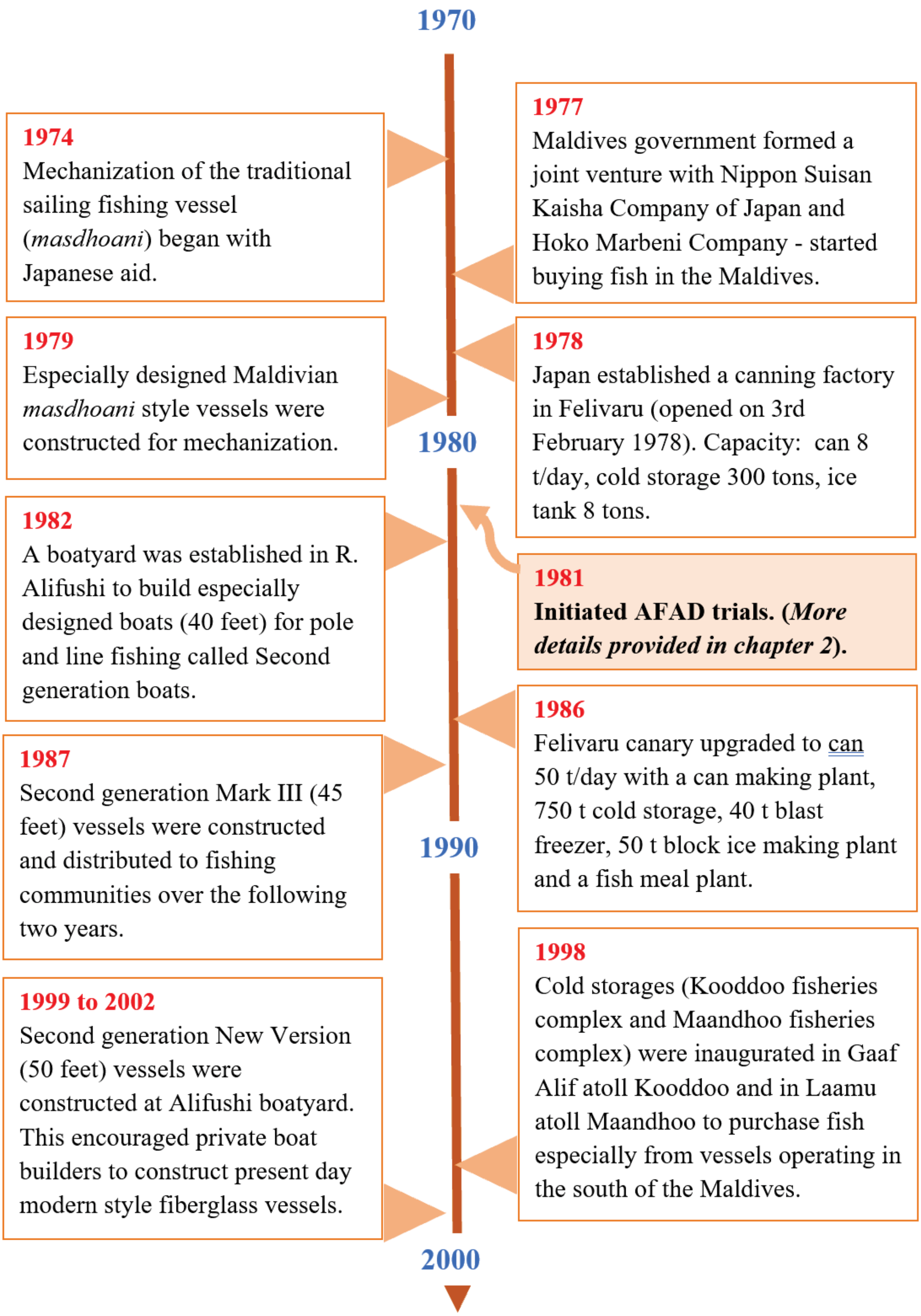


Figure 1.11: Timeline of the initiatives by the Maldivian government to expand the tuna fishery.

2.2 Tuna fisheries today

The traditional tuna fishery, which was an artisanal fishery that harvested tuna for mainly local consumption, has now evolved into a commercial fishery. The tuna catches have increased from a few thousand tons in the early 1970s to several hundred thousand tons per year (Naeem, 1994). There are four components in the modern Maldivian tuna fisheries. The details of each fishing gear are given in the next section.

a) The most important is the livebait pole and line fishery targeting skipjack tuna (*Katsuwonus pelamis*). This fishery was Marine Stewardship Council (MSC) certified in November 2012. Although the main target species is skipjack tuna, small yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*) are also caught in the fishery, representing approximately 15-17% and 5-10%, respectively (references?).

b) The second component is the handline fishery, which targets exclusively surface-dwelling large yellowfin tuna (fork length, FL > 70 cm). This fishery expanded since the early 1990s, when companies started exporting fresh yellowfin tuna loins. Several vessels that target large yellowfin using handline also carry pole and line gear with them. Depending on the type of school they encounter, they can easily switch gear, using pole and line gear for skipjack and small yellowfin (FL < 70 cm).

c) Longlining for tuna among the Maldives fishers is not very popular hence it remained a minor component. There was a licensed foreign longline fleet operating beyond 75 miles from the coast since 1985 (Anderson & Hafiz, 1996). Due to pressure from local fishers, licensing for foreign vessels was stopped in mid-2010. In 2011, the Government started issuing licenses for local longline vessels to operate beyond 100 miles from the coast and into the international waters. It was mandatory to use VMS and report their catch/effort using a logbook. In 2017, 44 such vessels were issued licenses. This fishery has been suspended by the government since July 2019.

d) A very small-scale troll fishery that targeted frigate tuna and kawakawa formed a substantial component of the tuna fisheries till the mechanization of the sailing vessels in the 1970s and 1980s. Troll fishery reached its peak during this time too (Anderson & Hafiz, 1996). Today there are small (15 to 20 m long), mechanized vessels conducting regular trolling activities for tuna especially, in those southern atolls where the livebait is scarce. They target both skipjack and yellowfin tuna.

It is also worth noting that since 2011, no foreign fishing vessel is allowed to fish in the Maldivian EEZ. Large nets such as purse seine, gillnets or trawls were never used in the Maldives. From time immemorial the Maldivian fishers have been using hook and line for tuna fishing, through pole and line, handline and trolling. The target species include skipjack, yellowfin, kawakawa, and frigate tuna. Bigeye tuna was targeted by the longline but mall quantities of juvenile bigeye tuna are caught during pole and line fishing.

2.3 Tuna fishing gear and methods

Pole and line

Over the centuries the pole and line fishing method has almost remained the same. The gear consists of a pole, a fishing line, and a barbless hook often with a lure. Though bamboo poles were used in the past, at present most fishers prefer to use fiberglass poles due to its strength and durability. One end of the monofilament line is attached to the pole while the other end is attached to the hook. The length of the line is almost the same as the length of the pole and breaking strain of the line varies depending on the size of the tuna being targeted. There are three different sizes of poles used – short (2 m), medium (3 m) and long poles (4 m). The choice of the poles selected for angling depends on how far the school stays from the vessel. If the school is very close to the vessels a short pole is used and if they tend to stay further away from the vessel a long pole is used for angling.

Fishing is carried out using livebait which is caught inside the atolls near coral reefs. Once adequate live bait is collected, fishers head out of the atolls into the open sea to look for tuna. Tuna schools are currently located with the help of binoculars, bird radars or by observing the movements of sea birds. Sometimes fishers head directly to fish at AFADs. As soon as the vessel arrives at a school of tuna, livebait is chummed and water is sprayed to attract the fish to the vessel and to slow the school (Figure 1.12). When tuna are near the vessel, angling begins from the back of the vessel. Fish caught on the barbless hook (Figure 1.13) are unhooked automatically as they fly on to the vessel (Figure 1.14) and land on the deck. The slacked line is quickly cast back into the sea. During a good fishing event one ton of fish could be caught in less than 10 minutes. During the whole angling process livebait is constantly thrown at the school.

Figure 1.12: Mechanical sprayers spray water as anglers catch tuna.

Figure 1.13: Locally made barbless hooks and lures.

Figure 1.14: When tension on the line is released tuna is unhooked automatically and lands on the deck.

Figure 1.15: Soon after a fishing event tuna are stored in holds with ice slurry in it.

Traditionally soon after an angling operation the fish are washed and kept on deck with belly side facing up to reduce fish belly burst. The fish on the deck are frequently splashed with salt water to keep them cool and to remove bacteria on the skin. Sometimes bait net is spread on the fish to prevent the hot sun from directly reaching them. Even today, the artisanal vessels do not carry ice on them but now the fish are kept in the main hold with seawater in it to keep the fish cool. These vessels mainly do day trips (leave port early morning and return by noon or afternoon) and sell their catch at the local markets in the inhabited islands.

Unlike the artisanal vessels, the commercial tuna fishing vessels carry ice or have refrigerated seawater (RSW) systems. During good fishing periods it is often difficult to get enough ice to conduct regular fishing trips and the RSW systems help these vessels to be independent from ice plants and companies that sell ice to the fishers. On modern pole and line vessels soon after the angling operation, the fish are washed and stored inside insulated holds in a slurry of ice or in RSW.

Handline

Traditionally, handline fishing was a common method of fishing practiced throughout the Maldives for mainly reef fishing except in Gnaviyani Atoll Fuvahmulah, where it was used for catching yellowfin tuna. Since the 1990s the greater access to overseas fresh fish markets led to the development of the yellowfin tuna handline fishery targeting only large yellowfin tuna (FL > 70cm) (M S Adam & Jauharee, 2009). By 1998 handline was widely used for catching yellowfin tuna in the Maldives as the export market expanded (Adam & Jauharee, 2009).

Handline fishing for large yellowfin is carried out on the same type of vessel as the pole and line vessels – the Maldivian *masdhoani*. There is no modification of the vessels, only the gear used is different. The handlines are made from about 100 m of monofilament fishing line (100 lbs to 150 lbs). One end of the line has a small, barbed hook (J-hook) while the other end is attached to a long nylon rope (200 m long and 2.5 to 4 mm in diameter). Depending on the size of the vessel, four to eight lines are operated simultaneously from the back of the vessel (Figure 1.16). Livebait is used for attracting and catching large yellowfin tuna. After arriving at the school, livebait is chummed to slow the tuna and attract them to the boat. Then lines are cast with a livebait hooked on it. Once the fish is hooked, it is pulled to the vessels. With the help of a gaff and/or a harpoon (Figure 1.17), the tuna is landed and quickly killed. The fish is then gutted, cleaned and stored in a slurry of ice (Figures 1.18 & 1.19).

Figure 1.16: Handlines for tuna are operated from the back of the boat.

Figure 1.17: A gaff or a harpoon is used to bring the fish on board.

Figure 1.18: After landing tuna guts and gills are quickly removed and fish is cleaned.

Figure 1.19: Large yellowfin are stored in a slurry of ice.

Trolling

In the past, troll fishing was popular in several atolls across the Maldives and contributed significantly to the total tuna landings. The sailing vessels (Figure 1.20) operated inside the atolls targeting mainly kawakawa and frigate tuna. Since mechanization of tuna fishing vessels began in the early 1970s the troll fishery has declined (Ahusan et al., 2018). But now there are some mechanized trolling vessels (Figure 1.21) that mainly target skipjack and yellowfin outside the atolls. The gear consists of long monofilament main line with several branch lines (up to 20) with lured hooks attached to it. There could be 3 such main lines operated by each vessel simultaneously. Once tuna are hooked the main line is pulled and the fish are manually unhooked and stored in ice.

Figure 1.20: Traditional sailing trolling vessel.

Figure 1.21: Modern mechanized trolling vessel.

2.4 Tuna fishing operation

A summary of the fishing operations is provided in table 1 below.

Table 1.1: Characteristics of the main tuna fishing methods/operations in the Maldives.

	Pole and line	Handline	Trolling
Target species	Skipjack and small yellowfin tuna (FL<70 cm)	Large yellowfin tuna (FL>70 cm)	Skipjack tuna, yellowfin tuna, frigate tuna and kawakawa
Targeted schools	AFAD, Free swimming, Log associated, Sea mounts	Dolphin associated, Free swimming	AFAD, Free swimming close to atolls
Zone of operation	From coast up to about 75 miles throughout the Maldives	Throughout the EEZ – but mainly from coast up to 150 miles	Inside the atolls and close to the coast (within 12 miles) outside the atolls
Duration of a fishing trip	Single day or multiday trips depending on the size of the vessel.	Multiday trips lasting about a week.	Single day trip – departs in the morning and returns before sunset.
Number of crew members	8 to 35 – depending on the size of the boat	12 to 20 – depending on the size of the boat	2 to 4
Vessel size	Artisanal – 10 to 20 m Commercial – 20 to 35 m	20 to 35 m	10 to 15 m
Catch disposal	Commercial companies and local markets	Commercial companies	Local markets
Main bycatch	Kawakawa, frigate tuna, small bigeye tuna and rainbow runner	Sailfish, marlin	Wahoo, dolphin fish, rainbow runner
Frequently used livebait	Sprats, cardinal fish, fusiliers and anchovy	Scads, fusiliers and red tooth trigger fish	None

In the Maldives tuna are caught by several hook and line gears using different sizes of vessels. Hence, tuna fishing operation varies depending on the scale of the fishing operation and the target species. The small (10 to 20 m) artisanal vessels (both pole and line, and troll) conduct single day trips while the large (>20 to 35 m) commercial vessels (both pole and line, and handline) do both single days trips and multiday trips depending on the distance between their fishing grounds and their home port. Both pole and line and handline fishing for tuna commences with livebait fishing activities. There is no livebait used during trolling for tuna.

Pole and line

A pole and line fishing operation can last a single day or several days depending on the availability of bait, weather and fishing condition (Figure 1.22).

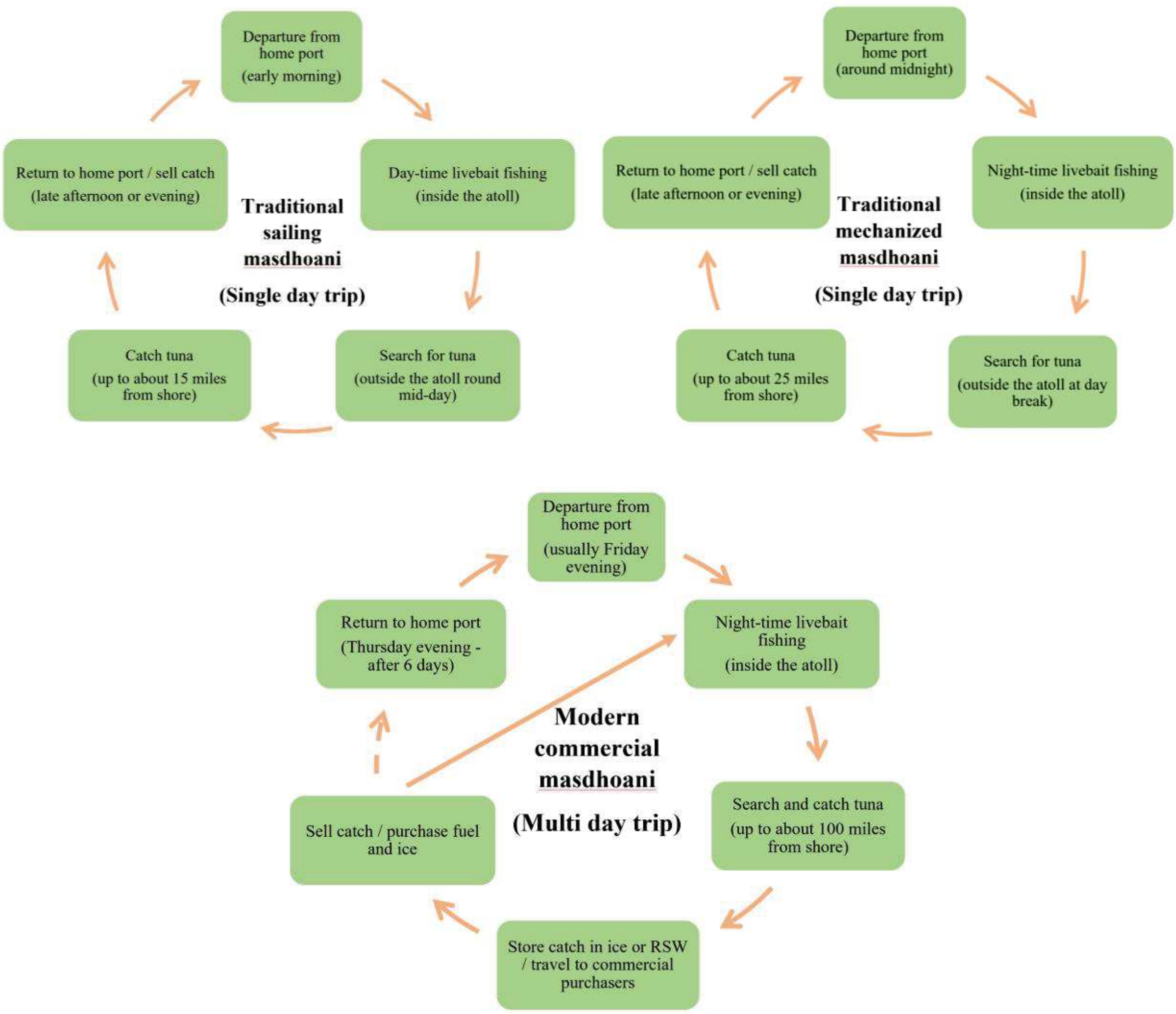


Figure 1.22: Typical fishing operations conducted by traditional sailing masdhoani (top left), traditional mechanized masdhoani (top right) and the present multiday commercial masdhoani (bottom).

During very good fishing periods, fishing is also affected by the various companies' ability to purchase fish as sometimes their storages can be full, and they frequently have to stop purchasing fish. If there is enough livebait and other supplies on the vessel, and if the weather is fine, fishers sometimes spend the night out in the open sea outside the atoll. The following day they continue fishing and return to one of the commercial tuna buyers inside the atolls. After selling the tuna to the commercial buyers, without returning to home port, they continue to harvest more livebait and head out to the open sea the following day. These fishing trips can last about 6 days before the vessel returns to its home port.

Although the modern commercial tuna fishing vessels are designed to travel in rough seas even during bad weather, these vessels do not venture very far from shore. Sometimes, they may go out to 240 km from the shore. Most of the fishing takes place close to shore – within 100 km from the shore (Figure 1.23).

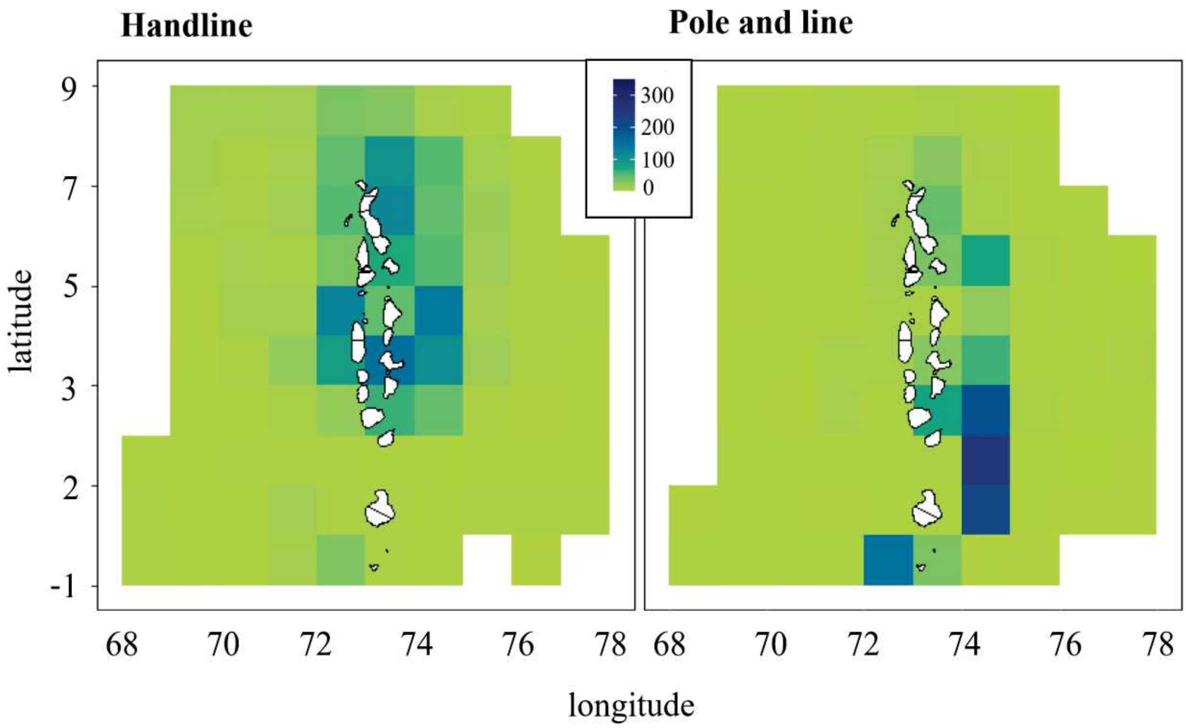


Figure 1.23: Distribution of fishing events for pole and line and handline gear – average for 2015 to 2019. (From pole and line and handline logbook data: MoFMRA).

Handline

The handline tuna fishers operate mainly in the north and central regions of the Maldives. This is mainly because the commercial buyers are based close to the international airport which is next to capital Male’ in the central region of the Maldives. Most large yellowfin tuna are exported by airfreight. The large yellowfin tuna fishers mainly fish from dolphin-associated schools and are known to travel frequently further away from the coast (sometimes more than 160 km). Some schools can be located just a few kilometers from the outer edge of the atolls while others are several miles offshore in the open ocean. The fishing operation may last from 3 to 8 days. Depending on the size of the vessel 4 to 8 handlines are operated simultaneously from the stern fishing platform. The tuna are caught at the surface (<10 m) and on average it takes about 10 minutes to pull it on board.

2.5 Tuna catches, bycatch and interaction with ETP species

The are five main species of tuna exploited by the Maldivian tuna fishers:

1. Skipjack tuna (*Katsuwonus pelamis*)
2. Yellowfin tuna (*Thunnus albacares*)
3. Bigeye tuna (*Thunnus obesus*)
4. Kawakawa (*Euthynnus affinis*)
5. Frigate tuna (*Auxis thazard*)

Between 2016 and 2020, the average catches of tuna correspond to 139,000 tons of tuna. The highest catches occurred in 2006, when the Maldivian fishers landed 167,000 tons of tuna (Figure 1.24). In 2019, the Maldives reported 134,300 tons of tuna catches. Skipjack tuna is the main target species in the Maldives, accounting for 66% of the catches in 2019, followed by yellowfin tuna (33%) (Ahusan et al., 2020). Most skipjack tuna (99%) and small yellowfin (FL < 65 cm) (38%) are caught by pole and line gear.

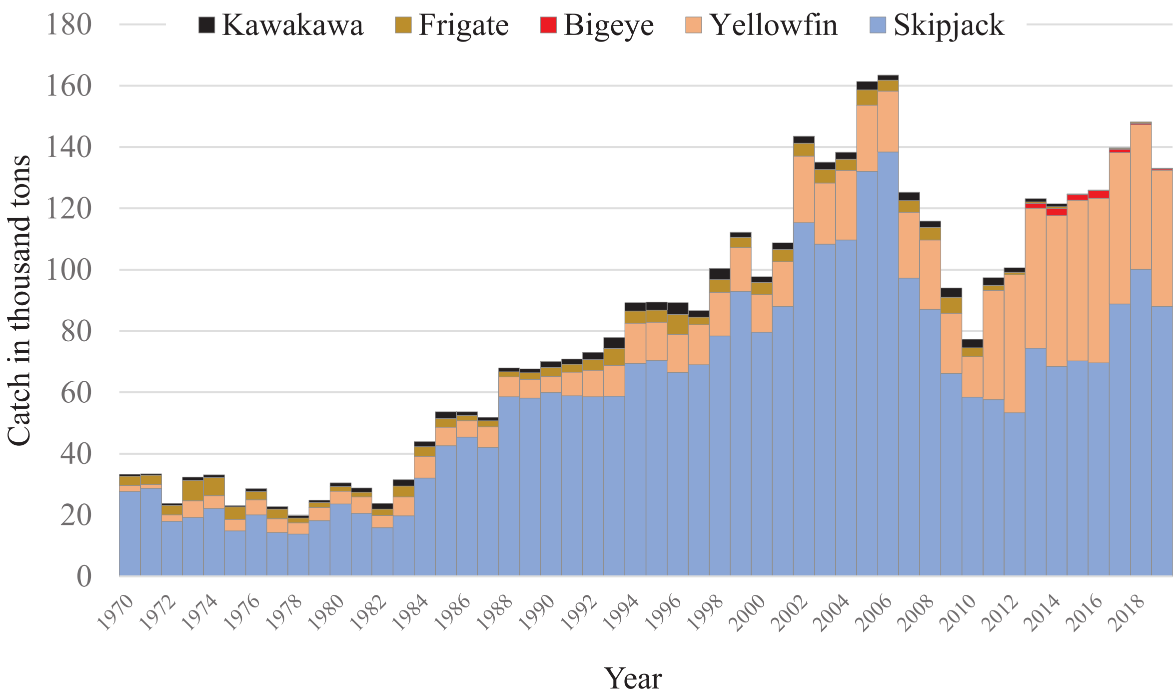


Figure 1.24: Tuna catches in the Maldives since the transition of the fishery began in the early 1970s to 2019.

In the south, where most of the commercial pole and line fishing takes place, the fishers target both skipjack and yellowfin tuna. The large commercial companies do not purchase neritic tuna, hence it is not useful for the big commercial vessels to target these species. Some amounts of neritic tuna are caught as bycatch in the skipjack pole and line fishery (Miller et al., 2017). The tuna catches follow a seasonal trend that depends on the monsoon seasons. Fishing is usually better in the northeast monsoon period (December to March) (Figure 1.25). During this period there are often limitations / restrictions on the amounts of fish that the companies buy from each vessel as the companies find it difficult to store or process all the fish landed by the fishers. Hence some vessels have to stop fishing during this peak period.

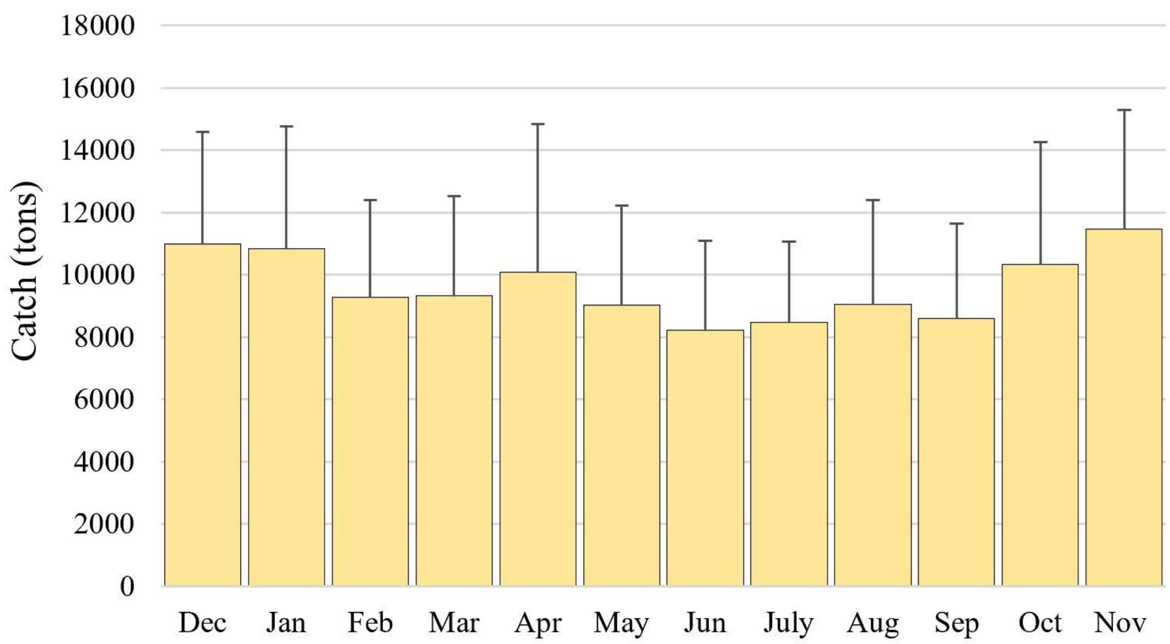


Figure 1.25: Average monthly variation in tuna catches and standard deviation estimated in the period 1985 to 2018.

Since 2010, the logbook also collects information on bycatch and endangered, threatened and protected (ETP) species associated with the tuna fishery. In addition to logbook data observers also work onboard fishing vessels to gather information on tuna catches as well as bycatch and ETP interactions during tuna fishing operations. It is very evident from these observer trips that there are very little or no discards in this fishery. The common bycatch species such as rainbow runner and dolphin fish are good food fish and are retained by fishers. The bycatch in the tuna fishery constitutes only 0.02% of the tuna catches (Miller et al, 2017). The interaction with ETP species are almost nil (Miller, Jauharee, Nadheeh, & Adam, 2016). Small silky sharks (*Carcharhinus falciformis*) are sometimes caught on the pole and line gear but are released alive, as shark fishing is completely banned in the Maldives since 2010. Observations made during observers' trips and from logbook data show very little or no injuries to ETP species such as marine mammals, sea turtles and other megafauna during livebait fishing operations (Jauharee, Neal, & Miller, 2015).

2.6 Fishing capacity and effort

The number of registered mechanized masdhoani (tuna fishing vessels) of all sizes is about 1000, however the number of active fishing vessels is far less (Figure 1.26). At present there are no sailing tuna fishing vessels (masdhoani). The 2014 Indian Ocean tsunami affected the fisher communities. Several fishing vessels were destroyed and fish purchasing companies were affected too. In the following years (soon after the tsunami), several efforts were made both by the government and the private sector to improve the fishery. Bigger vessels with better facilities helped accommodate more crew on the vessels and increase the fishing effort. On average 15 to 30 crews work on each vessel depending on the size of the vessel.

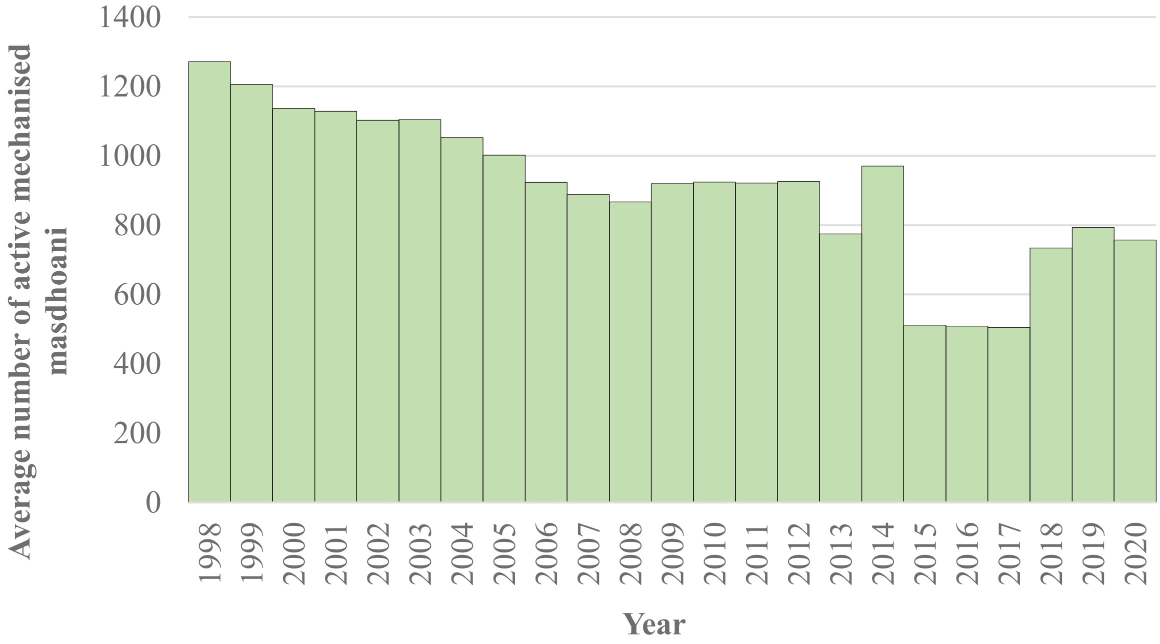


Figure 1.26: The average number of active fishing vessels (mechanized masdhoani) in the Maldives from 1998 to 2018 (Source: MoFMRA- based on reports received from atolls).

Although there was some increase in the number of trolling vessels in the 1980s their numbers declined sharply towards the end of the first decade of this century. This decline in both number of trolling vessels and mechanized masdhoani (both pole and line, and handline vessels) could be an indication of the socio-economic status of the communities. Fishing is still not a popular economic activity among the youth even though the income is reasonable. The increase in tourist arrivals and spread of tourist resorts to all parts of the Maldives have also opened new opportunities for the communities across the Maldives.

In small island communities across the Maldives, where job opportunities are limited, fishing provides a good source of income as well as food security for the fishers and their families. In the past the number of active fishers were at 15% of the total population but 2014 census showed it had decreased to about 5% of the total population. There has been a sharp decline in number of fishers working on the vessels (Figure 1.27) and it could seriously affect the sustainability of the fishery.

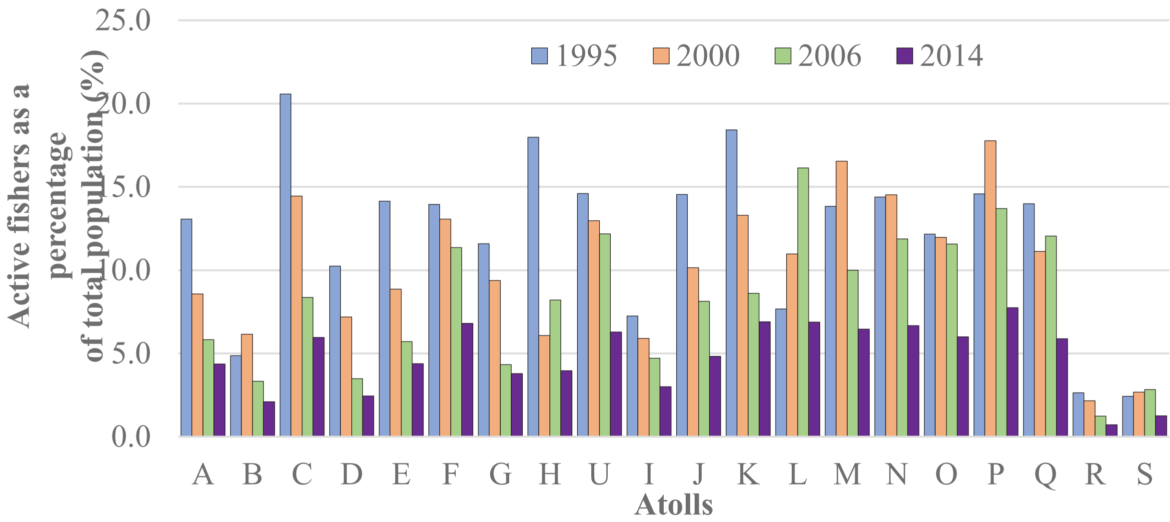


Figure 1.27: The percentage active fishers in different atolls during the years when the census was conducted in the Maldives from 1995 to 2014. The letters refer to Atolls – see Figure 1.1. (Source: NBS, 2020).

2.7 Vessel ownership, crew and income sharing

The tuna fishing vessels are owned by individuals or a small group of people such as a family. To construct a hull, to obtain the main engine and all the equipment, bank loans are frequently sorted. The vessels are constructed on local islands by local carpenters. Until recently tuna fishing vessels were constructed with wood but now fiber reinforced plastic (FRP) is used for construction. Family and relatives contribute and participate during the construction and operation of the vessel. There are no tuna fishing vessels owned and operated by any commercial companies.

Until recently it was illegal for expatriates to work as crew members on board Maldivian tuna vessels, but since 2021, under the new fisheries act (14/2019) two expatriates are allowed on each vessel. Some vessel owners have employed these foreign workers in tasks such as cooking for the crew and maintenance of the vessel. On-board modern fishing vessels the living conditions can vary, depending on the type of operation. Those vessels that conduct multiday fishing trips (Figure 1.10) have proper bunks for crew to sleep, toilets, fresh water, and a modern kitchen. On some vessels the crew accommodation is even airconditioned. The 15 to 30 crew members (depending on the size of the vessel) work as a team and take part in all the activities such as livebait fishing, angling during the landing of tuna and unloading the catch. On vessels that conduct day trips there is only a small shelter (Figure 1.9) where food and other necessary belonging are stored. Modern tuna fishing vessels are expensive (Table 1.2).

Table 1.2: Investment cost for three categories of pole and line tuna fishing vessels operated in the Maldives. (USD 1 = MVR 15.42)

Vessel name / launched year (Atoll. Island)	Randhi 2 2014	Faza / 2006 (E. Meedhoo)	Kandu Roalhi / 2016 (P. Gemanafushi)
Type	**Artisanal (Day trips)**	**Commercial (Day + multiday trips)**	**Commercial (Multiday trips)**
Length	15.5 m (51 feet)	25 m (83 feet)	34 m (111 feet)
Hull cost	MVR 425,000	MVR 700,000	MVR 1,800,000
Hull type	Wood	Wood	FRP
Crew accommodation	MVR 25,000	MVR 50,000	MVR 1,000,000
Engine type / Engine size Cost	Yanmar 3T / 200,000 39 hp	Daiwoo / 320 hp MVR 605,000	Daiwoo / 800 hp MVR 2,400,000
Generator / cost	2.7 kW / MVR 20,000	5kW / MVR 35,000	80 kW / MVR 400,000 50 kW / MVR 500,000
Pumps / cost	2 / MVR 20,000	4 / MVR 45,000	13 / MVR 270,000
Bait fishing light (W) / cost	1 (1000W) MVR 10,000	1 (2000W) MVR 25,000	6 (2000W) MVR 150,000 / 2 submersible (3000W) MVR 80,000
Dive equipment / cost	None	None	6 set + Compressor MVR 456,000
Diesel / week (liters)	100 liters	2000 liters	24000 liters
Ice required / week (tons)	None	5 to 8 tons	*25 tons
RSW system	None	None	2/ MVR 100,0000
Fish hold capacity (tons)	3 ton	10 ton	45 ton
Gear / week (cost)	MVR 200	MVR 700	MVR1000
Breakeven catch / week		3 tons	6 tons
Food / week (cost)	MVR 600	MVR 2500 to 3000	8-10, 000
Hull maintenance cost / year	MVR 20,000	MVR 750,000	MVR 100,000
Engine overhaul / 5 years	MVR 75,000	MVR 200,000	MVR 900,000
Engine maintenance / month	MVR 750	MVR 2000	MVR 5000
GPS	1 / MVR 11,000	2 / MVR 30,000	1 / MVR 38,000
Echosounder	None	MVR 30,000	1 / MVR 38,000
Communication equipment	1 VHF + Radio set MVR 11,000	1 VHF + Radio set 11,000	Satellite phone / MVR 16,000 VMS –MVR 7,800/year 2 sets – MVR18,000
Fishing poles + gear	MVR 65,000	MVR 80,000	MVR 120,000
Bait net	4 nets /	3 nets / MVR 24,000	3 nets / MVR 225,000
Anchor	2	3 / 18000	3 / MVR 150,000
Ropes	MVR 6000	MVR 15000	MVR 75,000
Bird radar	None	None	1 / MVR 350,000
Binoculars	1 / MVR 6000	2 / MVR 20000	3 / MVR 45,000
Number of fishers	6 to 9	14 to 18	25 - 35
Crew monthly income	MVR 5,000 – 7,000	MVR 10,000 to 12,000	MVR 10,000 to 15,000

Maldivian tuna fishers are never paid a fixed salary. In the traditional Maldivian tuna fishery, fishers were 'paid' with tuna. The catch was shared according to an agreed system. In non-mechanized, sailing boats the owner's share was one third of the catch and an additional share (equivalent to a share of the crew members) was taken to cover the cost on fishing gear and for the maintenance of the vessels. This system was revised at the beginning of mechanization to account for the running expenses such as fuel. After mechanization of the vessels began, a large deduction was made for the cost of fuel. In a study conducted in 1986, it showed that the crew members received MVR 1200 (USD 800) per month (Naeem, 1988). At present, skipper and crew are in a much better position and receive a higher share of the catch as the companies are paying a better price for the fish.

Today the distribution of income from fishing has also change. In many fisher communities, after deducting for the fuel and other expenses (operation costs) for the fishing trip, the remaining income is divided into three equal parts. One third of the income is for the vessel owner and the remaining two third are shared by the crew. A share equivalent to the share that each individual crew member gets is also provided by the vessel owner as an additional share from the boat owner's share to the captain. Hence captain gets an amount equivalent to two shares of the crew members. Other, slightly different sharing methods can also be seen among different fishing communities. Today, those working in the commercial tuna fishery earn between MVR 8000/- to 15000/- (USD 550 to 1000) a month on average. The income is distributed among the crew at the end of each week.

3 Livebait in the tuna fishery

Livebait used in the Maldives consists of small reef-associated species that are sourced from inside the atoll. Maldivians have been using livebait in the pole and line tuna fishery for over 1000 years (Gillett, Jauharee, & Adam, 2013). Each vessel carries several hundred kilos of livebait in their bait well or hold during every tuna fishing trip. The livebait is chummed to attract tuna and excite a tuna school into a feeding frenzy.

3.1 Gear and fishing technique

In the past, livebait was caught during the daytime, but now most of the livebait fishing takes place at night (Jauharee et al., 2015). The livebait is caught within the atoll lagoon inside the atoll or close to the shallow reefs. The main gear used for livebait fishing is a rectangular lift net. In the past this net was small and made from cotton, but today about 18x25 m nylon nets are used. There are two basic techniques used in this fishery for targeting pelagic and demersal species. During the daytime fishers locate these schools with the help of masks. Swimmers get into the water and look for schools of sprat at the surface or for fusiliers and cardinal fish on the reef slope sheltering near corals. In targeting pelagic species such as sprat, two long poles are attached to the net. The net is dipped into the water below the aggregations and lifted trapping the livebait. While targeting benthic species long ropes and lead weights are used to sink the net to the bottom of the sea (Figure 1.28). Chum (fish fillets) are placed by a swimmer in the water inside the rectangular net to attract bait onto the net. As the bait gathers to feed on the chum the net is raised trapping the small bait fish.

At night echosounders are used to locate bait school. Powerful lights (2000 W x 4) (Figure 1.29) are kept lit from one side of the boat for several hours to attract the baitfish. When the aggregation becomes large, the net is slowly lowered from the side of the boat and lifted trapping the fish inside it. For bottom dwelling bait species, the net is lowered from the edge of the boat all the way to the bottom of the sea. Once the net touches the bottom the net is spread out by fishers in the water with the help of ropes attached to the net. These fishers can be on the surface of the water or if the water is very deep (40 to 60 m) they dive using SCUBA gear. Often the net is set in water depths exceeding 25 m. All fishers (those in the water and on the boat) work in unison to pull the net towards the surface. Once the net is at the surface, livebait is quickly transferred to a flooded hold on the vessel using large scoop nets (Figure 1.30).

Figure 1.28: Day-time livebait fishing. The rectangular net is operated by swimmers in the water and fisher on the vessel.

Figure 1.29: Night-time livebait fishing using powerful lights targeting pelagic species such as sprat and anchovies does not require swimmers in the water.

Figure 1.30: Night-time livebait fishing targeting benthic species such as cardinal fish require swimmers in the water. The bait is transferred into the tank with scoop nets.

3.2 Livebait species

There are over 40 different species of small fish used as bait across the Maldives (Anderson, 2009) but only a few species are exploited regularly by fishers. Some of the qualities that fishers look for in a livebait species include its size, ease of catch and hardiness. The most important and extensively utilized bait species is the silver sprat (*Spratelloides gracilis*). This pelagic species is small, abundant, and easy to catch and readily attracts tuna when chummed. Other frequently used species in the pole and line tuna fishery includes several species of cardinal fishes, fusiliers, anchovy and blue sprat.

Table 1.3: Common livebait species used for catching tuna in the Maldives. (PL=pole and line, HL=handline / Juveniles of some species of bait fish used in the HL fishery are used in PL fishery)

English Common Name	Family/Species	Local Name	Fishery Used
Silver sprat	*Spratelloides gracilis*	*Rehi*	PL
Blue sprat	*Spratelloides delicatulus*	*Hondeli*	PL
Cardinalfishes	Apogonidae	*Boadhi, fathaa*	PL
Anchovy	*Encrasicholina heteroloba*	*Miyaren*	PL
Fusiliers	Caesionidae	*Muguraan*	PL and HL
Chromis	*Chromis* sp.	*Nilamehi*	PL and HL
Silversides	*Atherinidae*	*Thaavalhu*	HL
Bigeye scad	*Selar crumenophthalmus*	*Mushimas*	HL
Mackerel scad	*Decapterus* sp.	*Rimmas*	HL
Red tooth trigger fish	Balistidae	*Kalhu Rondu*	HL

The pole and line fishers who target small tuna (~30cm to 60cm FL) prefer to use small size bait fish such as silver sprat (*Spratelloides gracilis*), blue sprat (*Spratelloides delicatulus*) anchovy (*Encrasicholina heteroloba*) and cardinal fishes (Apagonidae) while the handline fishers targeting large tuna (>80cm FL) use larger sized bait fish such as round scad (*Decapterus macarellus*), bigeye scad (*Selar crumenopthalamus*) and red-tooth trigger fish (*Odonus niger*). Reef fishers also use relatively large bait fish.

3.3 Livebait catches

The size of the livebait fishery has increased over the years (Jauharee et al., 2015). Use of livebait by other fisheries other than pole and line tuna fishery has created additional demand on the resource; various forms of reef fishing and the yellowfin handline fishery require large quantities of livebait on a regular basis. In addition, some baitfish, particularly sprats and scads, are now routinely caught and landed on Malé fish market as a food fish increasing total livebait catch. In the mid-2000s total estimated bait catch was about 15,000 tons per year (Anderson, 2009). The expansion of large yellowfin handline tuna fishery has lowered the pressure on the livebait used by the pole and line tuna fishery. In 2014, the estimated bait catch by the pole and line tuna fishery was around 10,000 t (Jauharee et al., 2015). Livebait consumption in the Maldives tuna fishery is one of the highest: 11 kg of tuna per kilogram of livebait (Jauharee et al., 2015).

Most of the targeted species for livebait have short generation times and a high population turnover, although some livebait is likely to consist of juveniles (e.g., cardinal fish) (Anderson, 1997). The availability of livebait species varies greatly between seasons and regions throughout the Maldives which, combined with the large quantities required per fishing trip and year-round fishing, have resulted in fishers complaining about shortages of live bait (Anderson, 1997). Despite data collection methods for the tuna fishery being well developed as early as the 1960s, there was no routine data collection for the livebait fishery, but several efforts were made to document the live bait fishery. Reports produced by Anderson (1997), Adam (2006), Anderson (2009) and Gillett (2012) illustrated the livebait fishery in the Maldives. In 2010, logbooks (Figure 1.31) were introduced to collect fishery data. This initiated a routine formal data collection effort on the livebait fishery linked to the tuna fishery.

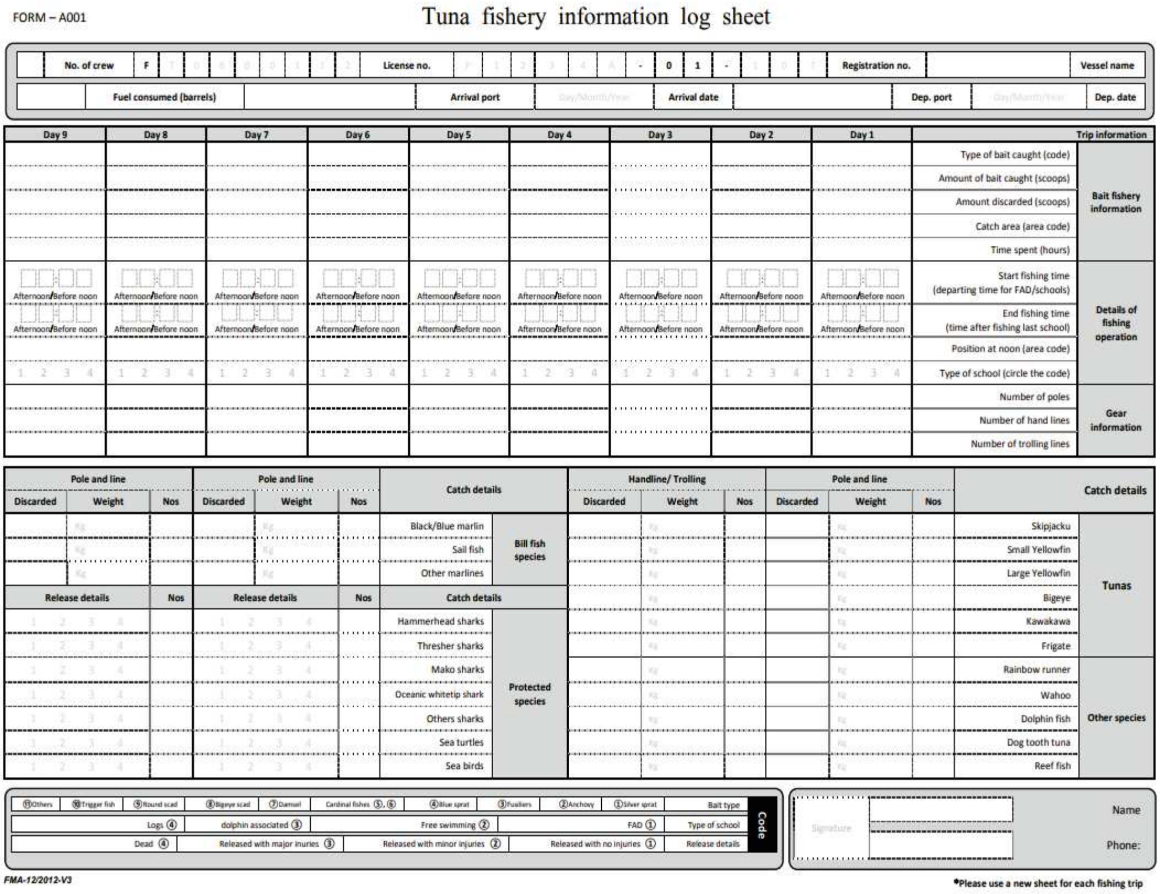


Figure 1.31: Log sheet filled by tuna fishers for every fishing trip (English translation).

4 Management

In the Maldives, the fisheries management is a responsibility of the government, mandated to the Ministry of Fisheries and Agriculture (MoFMRA). Due to various challenges in implementing the fisheries regulations, fisheries management is often limited to complete bans, prohibitions, export quotas, fees for exploitation of resources and licensing schemes. At present, the MoFMRA is assigned the responsibility of monitoring fisheries-related activities, formulate necessary regulations to ensure the sustainable exploitation of stocks and to enforce these regulations across the country. The Maldives Police Services and the coast guard help identify those that breach the regulations. It is now mandatory to have Vessel Monitoring Systems (VMS) on all licensed tuna fishing vessels which would help better monitor their activities.

4.1 Data collection

In the past, when fishing activities were concentrated around their local island and vessels returned to their island ports daily fisheries, data were collected from the island offices and share with the ministry. As the fishing activities expanded and several vessels got engaged in multiday fishing trips, it was necessary to introduce logbooks to collect data. Since 2010, data on tuna fishing operations are collected through logbooks. Fishers have to submit their logbook sheets (Figure 1.31) to the companies before they can proceed with unloading their catch. Data collected from fishers are aggregated and published by the National Bureau of Statistics (NBS) of Ministry of Housing and Infrastructure, on a dedicated Maldives website available for public access. This information is also submitted to the Indian Ocean Tuna Commission (IOTC) as part of mandatory data submission and in their annual national report.

The quality of the data is less reliable for the minor tuna species. According to Ahusan & Adam, (2015), a large percentage of the neritic tuna are caught by smaller vessels (15 to 20 m) and are not reported, making it difficult to account for the total tuna landings in the Maldives. Hence, it is difficult to account for the exact amount of tuna catches in the Maldives. To fully understand and manage the tuna fishery in the Maldives, the under-reporting of catch data needs to be addressed. This may be best achieved with the help of observers in the field, collecting information on various aspects of the tuna fishery. Recent changes in submitting logbook data have improved the amount of data gathered on the fisheries. Now commercial companies will not buy the tuna unless a log sheet of the fishing activities were submitted.

Field officers employed by the ministry working at main fishing landing ports such as Felivaru cannery, Maandhoo cannery, Koodoo and tuna fishing vessels collect data on catch throughout the year. In addition, staff from the Marine Research Centre (MRC) now called Maldives Marine Research Institute (MMRI) regularly conduct field work on board fishing vessels and in fishing communities to gather information on tuna fishery as well as the livebait fishery associated with the tuna fishery. This information is used to obtain an in-depth perspective of the fisheries. Tuna tagging activities to study the migration of tuna by IOTC (Anderson, Adam, & Waheed, 1996) and acoustic tagging studies to understand the behaviour of tuna around AFADs were some of the research activities conducted in the past (Govinden et al., 2013). The findings from these tagging activities also highlighted the importance of coastal countries working together to manage the tuna stocks. MRC has also collaborated with international research institutions to better understand the tuna fishery in the wider Indian Ocean.

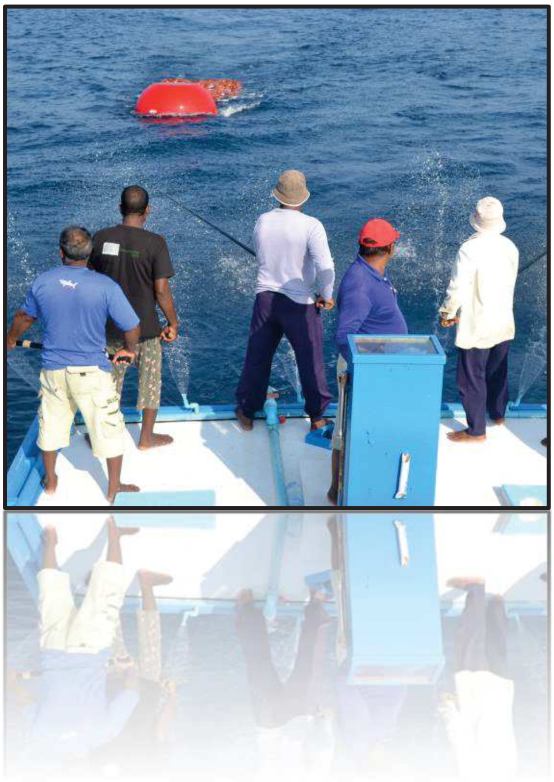
4.2 MSC certification and international cooperation

Eco-labels provide an assurance to customers of the responsible nature of the fisheries. Maldives has harvested tuna one-by-one for several centuries and is continuing its effort to ensure the resilience of the tuna stocks in the Indian Ocean and the sustainability of this fishery. The migratory nature of tuna calls for cooperation among all parties fishing in the Indian Ocean. Over the years the tuna fishery has experienced occasional decline in catches, and this has prompted Maldives to engage and play a more prominent role in managing the tuna stocks. Thus, in July 2011 Maldives became a full member of IOTC and since then has actively pursued to engage with all parties fishing in the Indian Ocean to better manage the tuna stocks. In 2012, the Maldives pole and line skipjack tuna fishery attained Marine Stewardship Council's (MSC's) certification. This helped prove the responsible practices of the Maldives tuna fishery. The certification was pursued by the Maldives government to help fishers obtain a better price for their catch. In 2019 the government of Maldives has passed a new Fisheries Law and subsequently several regulations were formulated to help better manage various fisheries in the country.

5 Discussion and conclusion

Tuna fishing is a major activity for the Maldivian nation. For over a millennium, the Maldives has been exploiting tuna resources from its coastal waters and the Maldives tuna fishery has now been promoted as a model for other coastal states (Hohne Sparborth et al., 2015). Tuna species are targeted by hook and line in the Maldives, landing each tuna one-by-one. The Maldivian tuna fishery has helped ensure food security, provided job opportunities that ensured a steady income for fishers and distributed the wealth from the tuna resources to more families across the communities. Maldives government policies towards not using large scale nets for harvesting tuna and preventing foreign vessels from operating inside the Maldives EEZ has helped ensure and protect the local tuna fisheries within the country. To ensure that the tuna stocks last for future generations, Maldives has already started to engage with international organizations and develop management strategies to be practiced within its EEZ. Efforts are also underway to improve data collection in the tuna fishery through introduction of applications and VMS that could help fishers transfer information on their fishing activities through a digital platform. Various research initiatives with international collaborations have helped better understand the fishery and future initiatives are planned for widening MMRI research capacity.

Like many fisheries throughout the world there are several challenges to managing tuna resources in the Maldives. Some of these difficulties included: not being able to acquire reliable data; demand from various stakeholders to harvest more tuna, and challenges in implementing the regulations due to limited resources for monitoring and the vastness of the country. It is always difficult to ensure restricted harvesting of stocks hence there very frequently a complete ban or an open access approach to resource use is practiced in the Maldives. For example, it is believed that Maldivians has exploited sharks for over a millennia (Techera & Cannell-Lunn, 2019) but since 2010 there has been a complete ban on shark fishing in the Maldives EEZ in place. Thus, Maldives has become a huge shark sanctuary in the Indian Ocean, though there is some pressure from locals to open the fishery.



Chapter 2

Anchored FAD fishery in the Maldives

1 Introduction

Floating objects in the open ocean are known to aggregate pelagic fish (Castro et. al., 2002; Kingsford, 1993). This knowledge has been used by fishers all over the world to aggregate fish by deploying man-made floating objects, known as fish aggregation devices (AFADs), to ease the location of pelagic fish and facilitate their capture. Around 30 countries use anchored fish aggregating devices (AFADs) in the Atlantic, Indian and Pacific oceans to attract fish (Freon & Dagorn, 2000; Karama & Matsushita, 2019) and enhance catch rates of local fisheries (Tim Dempster & Taquet, 2006). In the Indian Ocean countries such as Indonesia, Comoros, Mauritius, and Maldives use AFADs to catch tuna and other pelagic species.

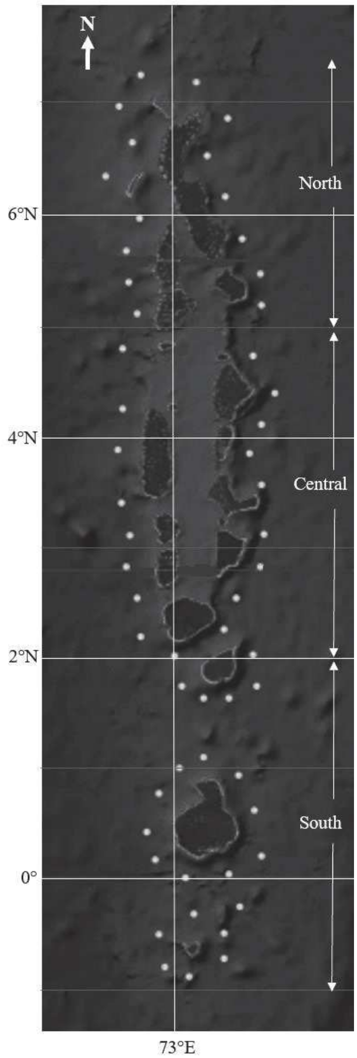


Figure 2.1: AFAD network outside the Maldives atolls. (White dots indicate location of AFADs outside the Maldives atolls).

For centuries Maldivian fishers have caught tuna schools associated to natural floating objects using pole and line gear. To expand the tuna fishery in the 1970s and 1980s the government took several initiatives. One of the initiatives was to deploy experimental AFADs locally known as "*Oivaali kandhufathi*". This experiment proved highly successful led to the development of the AFAD fishery in the Maldives. The following sections describe the evolution and management of this fishery.

2 AFAD design and development

The AFAD fishery in the Maldives began in 1981 with the deployment of experimental AFADs in the Maldives by the Ministry of Fisheries and Agriculture. The first experimental AFADs were deployed under a Food and Agriculture Organization (FAO) assisted project (Naeem & Latheefa, 1994a). The study looked at potential use of AFADs for attracting tuna and fishing. Initially, emphasis was given to the use of readily available materials and to use a simple deployment method. Overall, the production cost of AFADs were kept to a minimum with the use of locally available materials (Naeem & Latheefa, 1994b). Results of the first trials showed that the floats were unable to withstand the harsh environmental conditions hence the FADs were quickly lost. This design of floats lacked adequate buoyancy as the polyurethane filled floats absorbed water over time (Naeem, 1987).

The mooring lines used during the first study were 18mm polypropylene rope (3 strands). The scope (ratio of mooring line length to water depth) was exceptionally large, hence intermediate weights had to be used to submerge the anchor rope and this weight often got entangled with the rope. To begin with, concrete filled drums were used as clumped anchors for simplicity in construction and easy deployment but the cylindrical shape was thought to be a disadvantage resulting in a low holding power (Naeem, 1987). The AFAD losses during this initial stage of the study were mainly due to fish bite, abrasion, kinking and fouling (Naeem, 1998). Improper hardware selection and unprotected low-grade metal components resulted in severe corrosion contributing to loss of AFADs (Naeem, 1987).

Despite the high initial AFAD loss rate, fishers still found AFADs extremely useful and initial studies showed that AFAD fishing was highly successful (Naeem & Latheefa, 1994b). Thus 10 additional AFADs, sponsored by the United Nations Development Programme (UNDP), were deployed between 1985 to 1988 (Naeem & Latheefa, 1994b). Based on the success of these AFADs, today there is a network of 55 AFADs deployed around the Maldives.

Initially, fishers fully sponsored some of the AFADs but later the cost was equally shared by the private sector and the government. The first AFAD where the cost was shared by both the government and fisher community was deployed on 16th May 1993 outside the Maabaidhoo in Laamu Atoll. Since then, 30 similar AFADs were deployed (Naeem & Latheefa, 1994b). The government recognized that AFADs were very useful for the tuna fishery and since 2001 the government of Maldives decided that it would be a service provided by the government and all the expenses for construction and deployment will be covered by the government. Today constructing, deploying, and maintaining the AFADs are being carried out by the staff of Ministry of Fisheries and Agriculture (M S Adam, Anderson, & Hafiz, 2003).

3 Present AFADs

An AFAD has four functional elements: float or main buoy (Figure 2.2), attractors – small set of floats (Figure 2.3), the mooring line (Figure 2.4) and anchor (Figure 2.5) (Shainee & Leira, 2011). The float is a bright red buoy (2 m in diameter) built with a fibre glass shell and is filled with foam. Embossed on the buoy is the name "Ministry of Fisheries and Agriculture, Republic of Maldives" and a unique serial number for each AFAD printed at time of deployment. The mooring line is especially designed and imported from South Korea. The first 100 m of the mooring line from the buoy has an iron core. The concrete anchor and the stainless-steel attachments are made in the Maldives. All expenses (about USD 15,000 per AFAD) for construction, deployment, and maintenance of the AFADs are borne by the Maldives government.

Figure 2.2: FRP buoy that serves as the float for the AFAD with the Ministry and country name embossed.

Figure 2.3: AFAD deployed at sea – main buoy and set of floats at the surface.

Figure 2.4: Anchor rope with iron core.

Figure 2.5: Three-ton anchor made from interlocking concrete blocks.

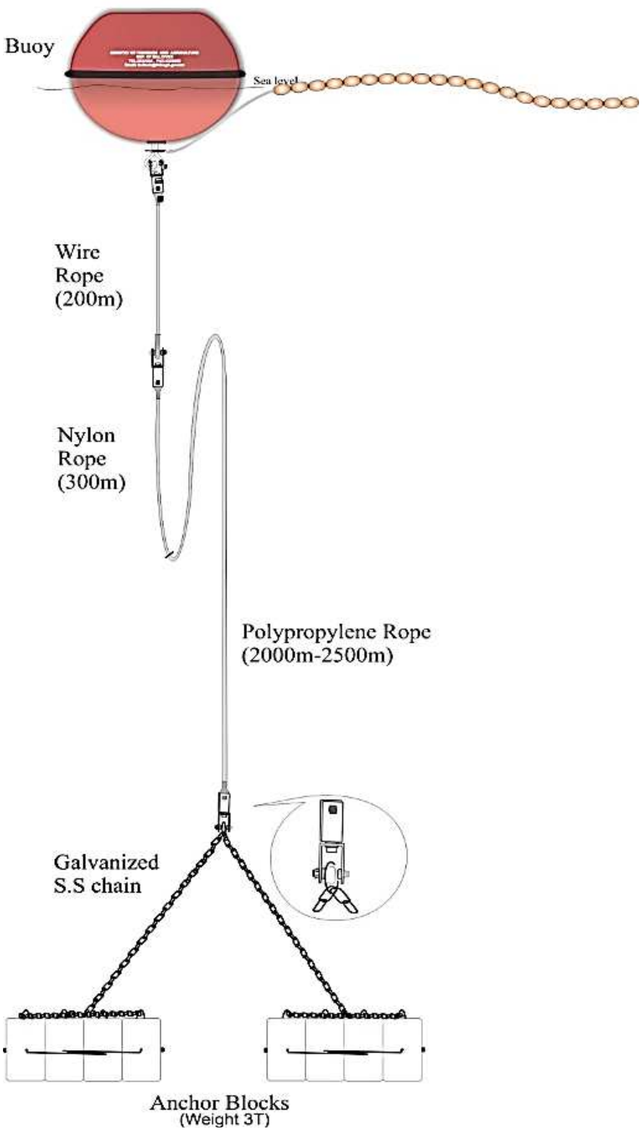


Figure 2.6: Present design of the AFAD used in the Maldives.

The present mooring system uses inverse catenary mooring which was achieved through application of a design recommended by the South Pacific Commission (SPC) (Naeem, 1988). This system uses nylon/polypropylene composite rope which does not require the use of counterweight. These were 20 mm in diameter with 8 strand braided rope in lieu of 18 mm diameter – 3 strand twisted rope. The braided ropes do not unlay due to the intricate construction. The corrosion problems with the hardware were overcome with the use of higher quality and larger shackles with locknuts. The anchor was modified to resist drag and to cope with high drag. The interlocking concrete blocks are linked using iron rods and welded together (Figure 2.5). The combined weight of the two anchor blocks is 3 tons. The floats were made larger (3.5 m) with fiberglass reinforced plastic (FRP) which increased the reserve buoyancy and increased its robustness to the adverse conditions of the marine environment. The "discus" shape float also had low drag (Naeem, 1988).

In the previous AFAD design, nets were attached as attractors: initially nylon livebait nets followed by larger meshed nets. These attractors were fixed between 10-15 m below the surface onto the main mooring line. Since 2013 the use of attractor nets was stopped which reduced the entanglement risk of the AFADs. The attachment used now to increase the floating surface area of the AFAD is a set of small floating buoys (350 of them threaded to form squared mesh with floats on each side – Figure 2.3) with netting fixed to lay horizontally underneath the floats. The net is not hanging and therefore highly unlikely to contribute to entanglement. Its function is to create a shade underneath the floats to give some sense of "protection" to the attracted fish (Figure 2.3).

4 AFAD deployment

By 2019 the total number of AFADs in the network increased to 55 AFADs. These AFADs are deployed about 20 km outside the Maldives atolls (Figure 2.1). The length of the rope used for anchoring varies from 1800 m to 3000 m depending on the depth. The AFADs are deployed by staff of the Ministry with community/fishers participation. The specific location for deployment of the AFADs are decided based on information gathered from community/fishers consultations and the echosounder surveys. AFADs were also deployed within a 2 hours distance from inhabited islands and a minimum of 24 km (15 miles) gap was maintained between any two adjacent AFADs. New AFADs replacing the old lost AFADs are almost always deployed at the same position.

The deployment is carried out using a fiberglass fishing vessel (Figure 2.7). Two large concrete anchor blocks are set up on both sides of the vessel on the stern platform (Figure 2.7). One end of the rope is attached to a chain which is linked to the anchor blocks and the other end of the rope is attached to the FRP float (main buoy). During deployment, first the buoy, attached to the anchor rope is deployed at sea (Figure 2.9) and the anchor blocks resting on the plank (on metal rollers) are then deployed (Figure 2.10). The rope kept on the deck of the vessel unlays as the anchor sinks to the bottom of the sea. The small floats that serve as attractors are also attached to the main buoy before it is deployed into the sea.

Figure 2.7: The vessel used for deploying the AFADs.

Figure 2.8: Concrete anchor block assembled on the vessel for deployment.

Figure 2.9: The main float attached with the set of small floats and anchor rope is first tossed into the sea.

Figure 2.10: Both anchor blocks resting on the deck of the vessel is simultaneously pushed into the sea.

In the present AFAD array (with 55 AFADs), the inter-AFAD distances between closest neighbouring AFADs range between 25 and 48 km. This choice by the Maldivian government for a low-density AFAD array appears to be unique as in other parts of the world, the tendency is to have denser AFAD arrays. There are no privately owned AFADs in the Maldives. The Maldivian government is responsible for managing and maintaining the AFAD array, and all AFAD positions are made public.

5 AFAD loss and recovery

There are several factors that contribute to loss of AFADs (Shainee & Leira, 2011).

1. Mooring line bitten by fish which include bites from large fish and foraging by various small fishes on fouling organisms on the rope.
2. Attachment failure including corrosion (wear and tear) of various metal parts.
3. Implosion of the float (main buoy) following prolonged immersion.
4. Anchor slipped into deeper waters and submerge as the anchor cannot hold the AFAD in position.
5. Propeller entanglement on the mooring line by large vessels.
6. Vandalism and fishers tying their vessels to the AFADs causing excessive strain on the mooring line.
7. More frequent and increase in intensity of storms.

Although several AFADs break from the anchor rope each year the buoys are often recovered by fishers and returned to the Ministry (Figure 2.11). In the past the rewarded was USD 65 (MVR 1000) for recovering and bringing the buoy on to the closest inhabited island. Since 2019, this amount has been increased and the reward is now USD 325 (MVR 5000) for the recovery of a buoy. The Ministry has started keeping records of recovered buoys since 2016. The lifespan of an AFAD is the duration from the date of deployment to the recorded date of detachment from the anchor or the date it got lost (M S Adam, Jauharee, Azheem, & Jaufar, 2019). By mid 2000s the average life span of the AFADs were 5 to 8 years but since then, it had started to decrease. This decrease could be related to the more frequent and prolonged severe weather events experienced in the Maldives. Hence Ministry is now experimenting with a larger float (buoy) and thicker ropes for mooring that could hopefully help prolong the lifespan of the AFADs.

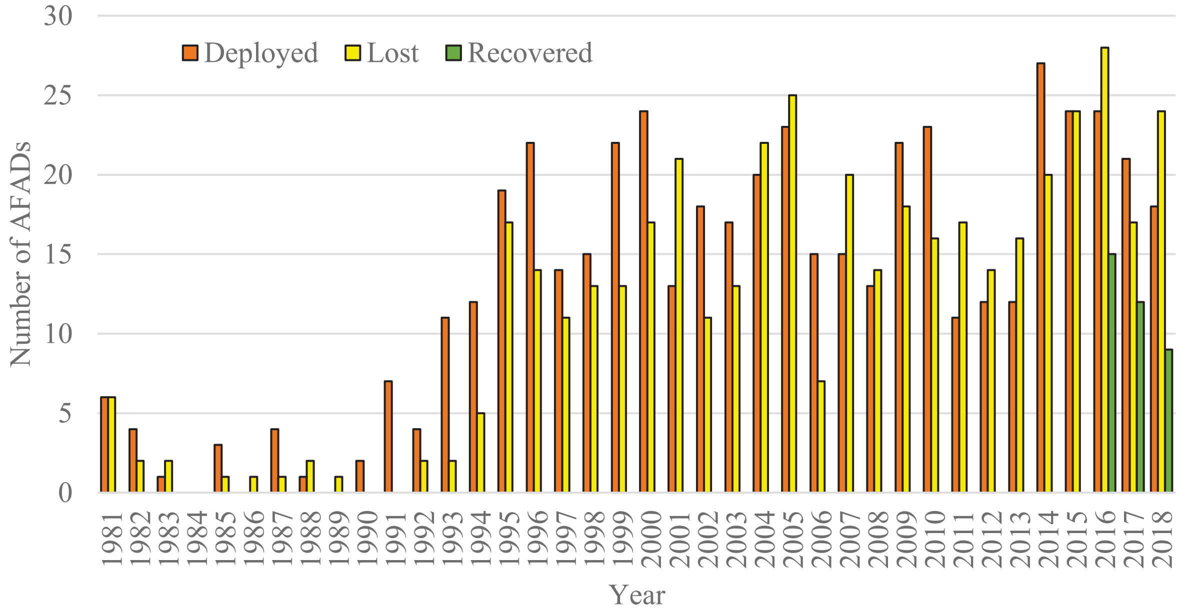


Figure 2.11: Number of AFADs deployed, lost (detached) and recovered since the program began in 1981.

6 Fish aggregations at AFADs

Once the AFADs are deployed, algae and several fouling organisms grow on the submerged structure of the AFADs. Small and large pelagic fish (i.e. tunas) can rapidly colonise the AFADs. Naeem and Latheefa (1994) reported sighting of several species of fish at the AFADs deployed in the Maldives within 3 to 4 weeks after it is soaked. A study conducted by Forget et al. 2020 investigated the diversity of the pelagic fish assemblages at AFADs in the Maldives and reported the presence of 19 non-tuna species including: *Caranx rnelampvgus, Elagatis bipinnulatus, Caranx sexfasciatus, Kyphosus vaigiensis, Decapterus macarellus, Abudefduf vaigiensis, Canthidermis maculatus, Aluterus monoceros, Coryphaena hippurus, Carcharhinus falciformis, Aluterus scripta, Acanthocybium solandri, Naucrates doctor, Carangoides ferdau, Platax teira, Carangoides orthogrammus, Seriola rivoliana, Remora remora, Echeneis naucrates, Sphyraena barracuda and Canthidermis maculatus* (F. Forget et al., 2020)(F. Forget et al., 2020). Tuna and tuna-like species found at AFADs include skipjack tuna *(Katusuwonus. pelamis), y*ellowfin tuna *(Thunnus albacares),* frigate tuna *(Auxis thazard) and* kawakawa *(Euthynus affinis).*

7 Fishing at AFADs

The only permitted method of fishing at AFADS in the Maldives is pole and line. There is a regulation stating that within a 3-mile radius of the AFADs, only pole and line fishing should be practiced. According to most pole and line fishers, the use of handline to catch large yellowfin around AFADs (sometimes even using bright lights at night) causes the school to disperse by next morning. Even during periods of particularly good fishing at the AFADs, if fishers use handlines, some fishers believe that the school leaves the AFAD by the following day.

Skipjack and yellowfin tuna are the most frequently caught major tuna species at the AFADs in the Maldives. Fish catchability greatly varied with no discernible pattern (Naeem & Latheefa, 1994a); however it is well known by fishers that the best time for fishing at the AFADs was at sunrise late in the afternoon, before sunset (Naeem & Latheefa, 1994a). All pole and line tuna fishers have equal access to all the AFADs. There are two categories of pole and line vessels using AFADs: the artisanal and the commercial (larger vessels ~ >25 m) (Figure 2.12). It is common practice among the artisanal (subsistence) fishers to fish at the AFADs regularly. They see several advantages in fishing at the AFADs:

- Increases the probability to catch fish.
- Since the AFADs are deployed close to fishing communities they can spend less time out at sea and quickly bring their catch to the port.
- They do not have to keep their catch in ice as fishers can quickly get back to port since the AFADs are close to the coast – saves money spent on purchasing ice and constructing insulated holds on their vessels.
- Fuel savings – hence reduce cost of operation since the search time for tuna schools is reduced.
- Makes it possible to spend more time with their family as they can return home more quickly.
- Provides food security and cheap source of good quality protein for the community.

Figure 2.12: Several pole and line vessels fishing at an AFAD in the Maldives.

Unlike artisanal fishers, the commercial pole and level vessels fish at the AFADs only when there is an abundance of medium to large tuna (>2 kg) present or if the vessel conducts day trips – that is leave the port and return to port after fishing on the same day. The multiday vessels use the AFADs if they cannot locate schools in the open sea (free-swimming schools, log associated schools or dolphin associated schools). When fishing in the open ocean is not successful, visiting and fishing at AFADs allows them to cover their daily expenses of the fishing trip.

The commercial fishers do not regularly fish at the AFADs for several reasons.

- The catch is often mixed sizes – i.e. both small and large tuna are caught. The commercial companies prefer to buy large tuna (> 1.5 kg) and they buy it at a better price than those less than 1.5 kg. Hence commercial fishers are discouraged in targeting small sized tuna. They prefer to fish at free swimming schools where there are bigger fish of similar size and less competition from other vessels out in the open ocean.
- When too many vessels fish close by and chum to attract the tuna, the school often fragments into small groups and small quantities of tuna follow every vessel. Hence fishers often have to use large quantities of livebait to ensure that more fish are attracted to their vessel. As a result, they quickly run out of bait too. To avoid such stiff competition and to ensure maximum use of livebait commercial pole and line vessels therefore prefer to fish free swimming schools.

The AFAD fishery help to ensure food security and provide employment opportunity for the local communities. In addition, AFADs help to sustain the pole and line fishery in the Maldives. Analysis of the 2019 logbook data showed that, of the 3745 fishing events that took place at the AFADs across the Maldives, more than 57% of them took place in the south. Catch data obtained by the Ministry also showed that nearly two thirds of the pole and line catches come from the south of the Maldives hence fishing is more intense in this region (see Chapter 1). From the 2019 pole and line logbook data it was evident that nearly 38% of the reported fishing trips took place at the AFADs (Figure 2.13).

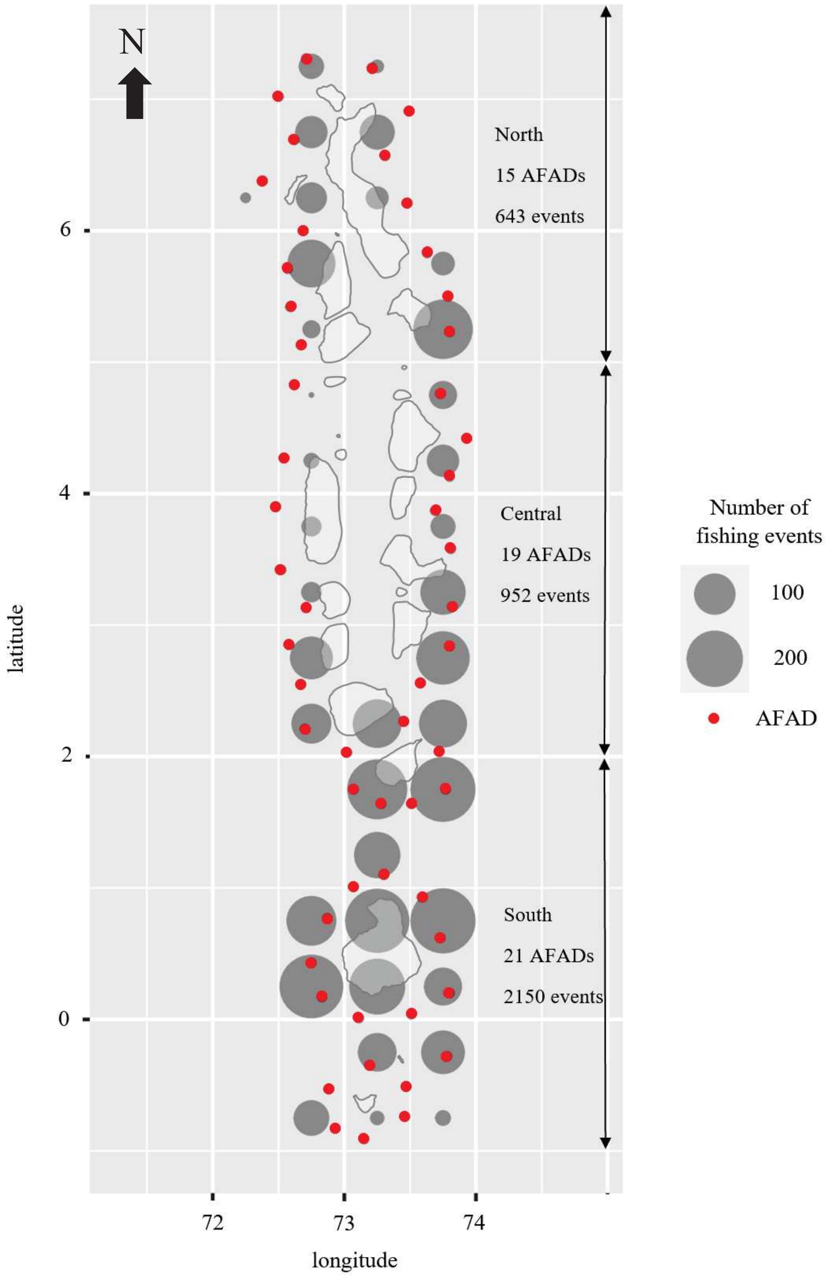


Figure 2.13: Number of fishing events per 0.5 degrees cells at AFADs in the north, central and south of the Maldives in 2019 (Logbook data, MoFMRA, 2020).

In the central and northern parts of the Maldives the number of AFAD fishing events are lower as there are more handline vessels targeting large yellowfin tuna (>20 kg) operating in these regions. Additionally, in the north, there is more limited opportunities to sell pole and line caught tuna (<70 cm FL) as there is only one tuna processing factory in the region. Although large yellowfin tuna are known to aggregate at AFADs, it is prohibited to use handline gear within a three miles radius of the AFADs. During a fishing trip, one or several fishing events at different types of schools can take place. Hence sometimes during the same fishing trip fishers may try to fish at AFADs after fishing at other types of schools such as log, dolphin, seamount associated or free-swimming schools. The number of fishing events that took place at the AFADs appear to be slightly higher during the northeast monsoon (December to March – Figure 2.14). During the southwest monsoon (May to October) the wind is strong and severe weather events are more frequent making it difficult for fishers to venture out to fish.

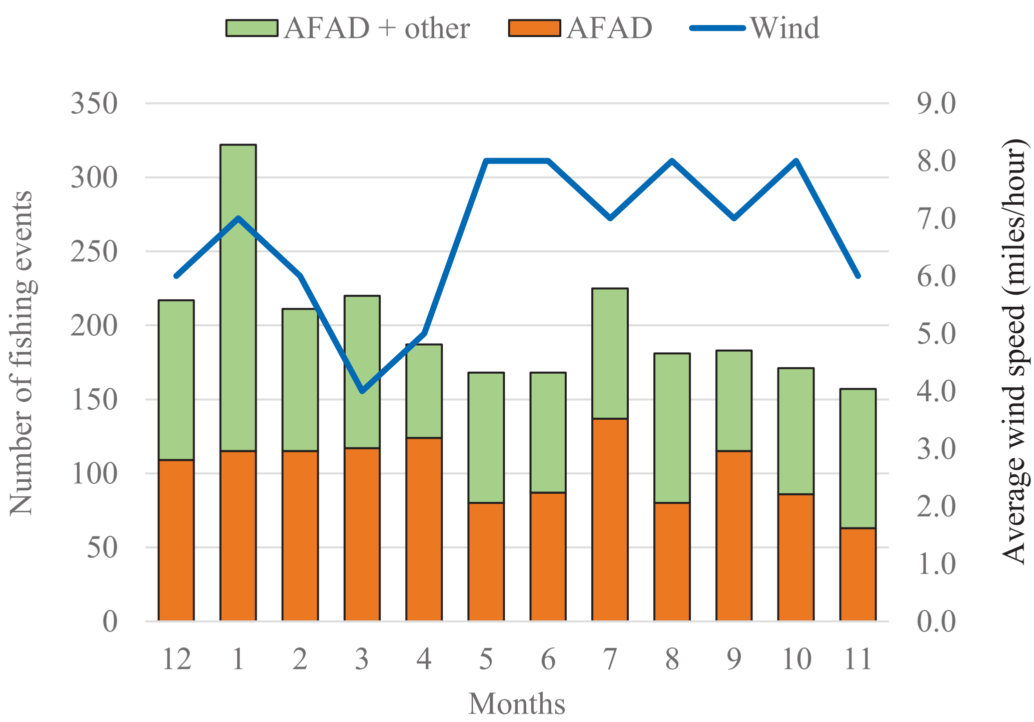


Figure 2.14: Reported number of fishing trips (by month) where fishing took place only at AFADs and at both AFADs and other schools during the same trip in 2019. The average wind speed for 2019. (Source: Logbook data, MoFMRA and wind data from NBS, 2020).

8 The AFAD catches

The initial field studies conducted by Marine Research Centre on AFAD catches showed that the national tuna catches increased from 30,000 tons in 1980s to 70,000 tons in 1990s. Today, the national catches exceed 100,000 and information on catches is gathered using a logbook system by the Ministry of Fisheries. Fishers report their fishing activities, catch and bycatch for every fishing trip on log sheets. Using this information and observer data, the Ministry estimates the amount of tuna caught at AFADs. It is estimated that about one-third of all the tuna caught in the Maldives are caught at AFADs (Miller et al., 2017). Most frequently caught species around AFADs in the Maldives are listed in Table 2.1. Skipjack and yellowfin tuna contribute to about 93% of the tuna catches at the AFADs. Although large yellowfin tuna (FL>80 cm) can sometimes be abundant at the AFADs, they are very rarely caught by pole and line gear.

Table 2.1: Tuna species caught at the AFADs in the Maldives (Source: Observer data from 2014 and 2015. MRC, 2015). The last column indicates, for each species, the percentage of catches relative to the total tuna catches at AFADs.

Common English name	Scientific name	Local Dhivehi name	%
Skipjack tuna	*Katsuwonus pelamis*	Kalhubilamas	49.1
Yellowfin tuna	*Thunnus albacares*	Reedhoouraha kanneli	44.0
Bigeye tuna	*Thunnus obesus*	Loabodu kanneli	3.7
Kawakawa	*Euthynnus affinis*	Latti	3.0
Frigate tuna	*Auxis thazard*	Raagondi	0.2

Skipjack, yellowfin and bigeye tuna are targeted by the fishers as they are the only species purchased by the commercial companies in the Maldives. The other species – kawakawa and frigate tuna - are caught as bycatch by the commercial pole and line tuna fishers but are targeted by the artisanal fishers. Since they all are good food fishes, fishers retain them, and they are either consumed or sold at the local markets. Other common bycatch species retained by fishers include dolphin fish (*Coryphaena hippurus*), rainbow runner (*Elagatis bipinnulata*) and round scad (*Decapterus macarellus*). There is a near zero discard in this fishery as the fish are caught one-by-one and all used. The catch mostly comprises of varying sizes of skipjack and yellowfin tuna. The most common size of tuna caught at the AFADs using pole and line have a fork length between 35 cm to 50 cm (Figure 2.15).

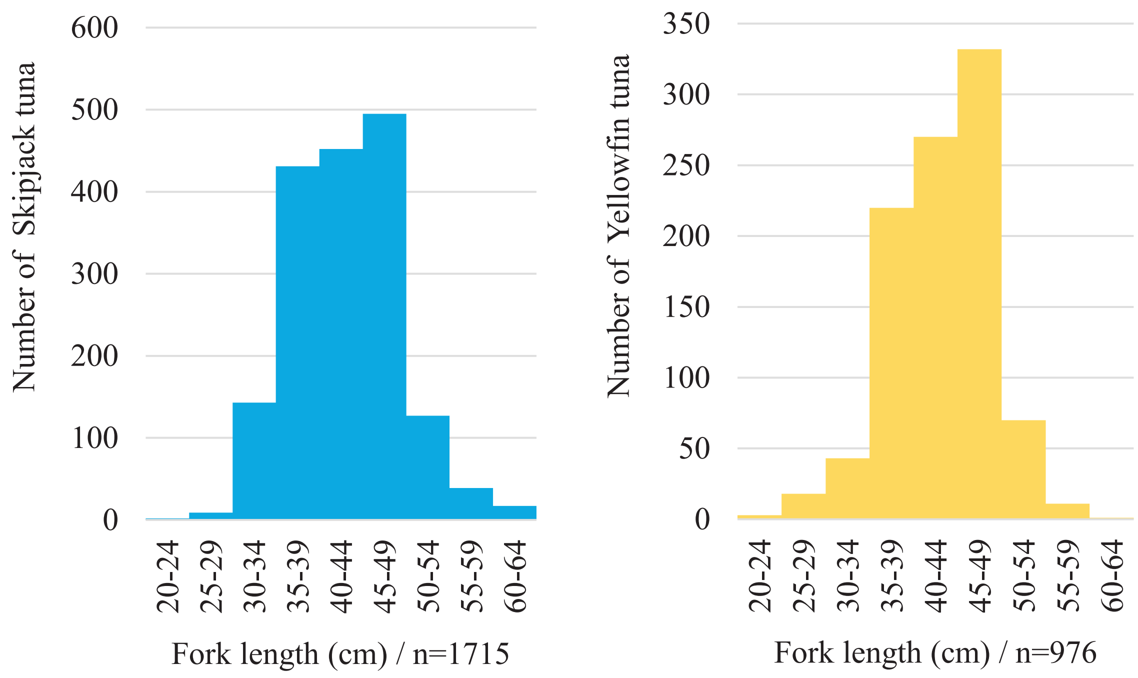


Figure 2.15: Size distribution (Fork length) of skipjack and yellowfin tuna caught at the AFADs. (Source: Observer data – 2014 and 2015. MRC, 2015).

9 AFAD fishery management

The Fisheries Ministry makes regulations on fishing activities taking place at the AFADs and the type of gear to be used at the AFADs. It is also illegal to conduct any activities that could have a negative effect on the pole and line AFAD fishery such as vandalism of the AFADs or use of inappropriate livebait that can influence the behaviour of tuna. Fishers who engage in such activities face penalties such as fines and cancellation of their fishing licences.

To regulate the AFAD fishery the government has taken several initiatives.

- The AFAD network around Maldives atolls is limited to 55 AFADs.
- The AFAD network is fully owned and managed by the government.

- The distances between neighbouring AFADs are kept exceptionally large (25 to 48 km).
- When a AFAD breaks off another AFAD is deployed at the same position.
- Over time changes were made in the AFAD design, to reduce their entangling potential.
- AFADs are clearly marked with the name of the management authority and a unique serial number.
- Incentives are provided to any party that recovers the AFAD hence reducing the amount of plastic pollution.
- Recovered AFADs are reused.
- AFADs are deployed about 12 miles from the outer edge of the atoll so less fuel is spent in accessing them.
- All pole and line fishers have equal access to all the AFADs across the Maldives.
- Data is gathered on fishing events at AFADs, species caught and their fork length using logbooks and observers.
- For internal audits and for research purposes records of deployments, loss and recoveries are maintained by the Ministry of Fisheries.

Maldives has also submitted an AFAD fishery management plan to the IOTC in 2014. The main objectives of this management plan include:

- Making necessary changes to the AFADs to minimise incidences of entanglement.
- Collecting and sharing deployment and lost AFADs information
- Strengthening surveillance of fishing activities near AFADs

This management plan applies to all licensed tuna fishing vessels that used the AFADs and the government is responsible for implementing the actions in the management plan. Information on fishing activities at the AFADs are collected through the logbooks that fishers are required to submit. Failing to submit this information can result in termination of fishing licenses preventing them from selling their catches to exporters or commercial companies that purchase tuna.

10 Conclusion

The use of AFADs has had several positive effects on the fishers' communities. It has increased fishers' income by reducing search time for tuna schools thus reducing the amount of fuel spent. It has helped ensure food security to many communities across the Maldives. Even during severe weather fishers are almost guaranteed to catch tuna not too far from their home port. In addition to increasing the overall national tuna catch, AFAD array has helped sustain the pole and line tuna fishery in the Maldives by ensuring catches even during days of poor fishing out in the open ocean. This AFAD fishery has provided income generating opportunities especially for those rural island communities both directly (for those working on the fishing vessels) and indirectly (through various processing industries and other businesses affiliated to the fishery).

The main challenge facing the government is the lack of scientific knowledge on the dynamics of fish aggregation and their behaviour at these AFADs. Such information may help to better manage the AFAD fishery sustainably and reducing the ecological impacts while ensuring maximum yield. There is also pressure from the local fishers (both recreation and tuna fishers) to increase the number of AFADs in the array but since only few studies were ever conducted on the aggregations at the AFADs it is rather difficult to postulate on the possible consequences of increasing the number of AFADs or moving them closer or further away from the coast. At present the government is cautious in increasing the number of AFAD in the Maldives. Additional studies need to be conducted to provide science-based advices for sustainable AFAD fisheries in the Maldives.

Chapter 3

Tuna behaviour at anchored FADs inferred from Local Ecological Knowledge (LEK) of pole and line tuna fishers in the Maldives

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Abstract

The Maldives tuna fishery landings in 2018 were 148, 000 t and accounted for nearly a quarter of the global pole and line tuna catch. This fishery partially relies on a network of 55 anchored fish aggregating devices (AFADs) deployed around the archipelago. About one-third of the total pole and line tuna catch is harvested at AFADs. Although the AFAD fishery has existed for 35 years, knowledge on the behaviour of tuna in the AFAD array is still limited, precluding the development of science-based fishery management. In this study, local ecological knowledge (LEK) of fishers was used to improve our understanding of tuna behaviour, through personal interviews of 54 pole and line fishers from different parts of the archipelago. Interview results suggest that during the northeast monsoon tuna are more abundant on the eastern side of the Maldives, while during the southwest monsoon they are more abundant on the western side of the Maldives. Most fishers believed that tuna tend to stay at the AFADs for 3 to 6 days and remain within 2 miles from the AFADs when they are associated. Fishers believe that strong currents is the main factor for tuna departure from AFADs, though high sea surface temperatures and stormy conditions were also thought to contribute to departures. Moderate currents are believed to be a favourable condition to form aggregations at the AFADs while other factors such as suitable temperature, prey and attractants enhance this aggregation. Fishers also believe that there are multiple schools segregated according to size and species at AFADs and that catchability is higher at dawn and in the late afternoon when the tuna occur shallower in the water column. This study is an important step towards engaging the Maldivian tuna fishers into a science-based fishery management

1 Introduction

Understanding fish behaviour is a key element of scientific expertise to assist in stock assessment and fisheries management (Freon & Misund, 1999). Behaviour structures the spatio-temporal distribution of fish in three dimensions and defines their accessibility and vulnerability to fishing gear. Collecting information on the behaviour of pelagic fish is quite challenging because of the difficulties in accessing these animals in their natural environment. The vast majority of the scientific knowledge on the behaviour of pelagic fish has been acquired through acoustic devices (sonars), visual devices (aerial surveys or cameras) and electronic tagging. These techniques, however, are expensive and require advanced scientific expertise. These constraints can limit their use, particularly in developing countries.

It is widely known that fishers spend a lot of time observing, understanding and accumulating information on fish behaviour (Baird & Flaherty, 2005; Johannes & Neis, 2007; Lavides et al., 2010). Their fishing efficiency partly depends on this knowledge. Local Ecological Knowledge (LEK) or Fishers Ecological Knowledge (FEK) has therefore been used to make this knowledge available to science, as an alternative source of information (Ruddle & Davis, 2013). For instance, LEK has been used to study migration (Valbo-Jørgensen & Poulsen, 2000), spatial distribution (Poizat & Baran, 1997), habitat use (Silvano & Begossi, 2012), meso-scale behaviour (Mackinson, 2001), and fine-scale behaviour of fishes (Moreno, Dagorn, Sancho, & Itano, 2007).

Several pelagic species, including tropical tuna, are naturally attracted to floating objects such as drifting logs or marine debris (M. J. Kingsford, 1993). Although several hypotheses have been postulated to explain the associative behaviour of tuna (Jaquemet, Potier, & Ménard, 2011), including the meeting point hypothesis (Freon & Dagorn, 2000; Soria, Dagorn, Potin, & Fréon, 2009) and the indicator-log hypothesis (Hall, 1992), we still do not know why tuna associate with these objects. Naturally, this has not prevented fishers from taking advantage of this particular behaviour to help them find and catch tuna. The Roman author Oppian (200 AD) first reported catches of pelagic fish around floating objects in the Mediterranean sea, while aggregating devices were used in Japan in the 17th century (Nakamae, 1991). The use of floating objects by fishers developed considerably in the 20th and 21st centuries with the expansion of fisheries targeting tropical tuna and the use of Fish Aggregating Devices (FADs). FADs are man-made objects built and deployed for the purpose of fishing. FADs contribute to increase the catchability of tuna and other pelagic species (Marsac et al., 2000a). There are two types of FADs: drifting FADs (DFADs), usually equipped with electronic buoys to remotely locate them and sometimes send information on the quantity of associated fish (J Lopez, Moreno, Sancristobal, & Murua, 2014), exploited offshore by industrial purse seiners, and anchored FADs (AFADs), primarily used near the coasts by small-scale fisheries (L Dagorn et al., 2013).

Because FADs play such a major role in the efficiency of tuna fisheries, they must be properly managed. Regional Fisheries Management Organisations (RFMOs) such as the Indian Ocean Tuna Commission (IOTC) have therefore prioritized the establishment of FAD management plans (IOTC, 2014) to ensure the sustainability of fisheries. Just like the technical and socio-economic characteristics of a fishery, or the functioning of the ecosystem, the behaviour of fish is a scientific knowledge necessary to establish coherent FAD management plans. The behaviour of fish at FADs has been investigated through acoustic devices (e.g. (Brehmer et al., 2019; Doray, Josse, Gervain, Reynal, & Chantrel, 2006)) and electronic tagging (e.g. (Laurent Dagorn, Holland, & Itano, 2007; Ohta & Kakuma, 2005; Robert et al., 2013; Rodriguez-Tress et al., 2017)). LEK was also used to inform on the behaviour of tuna at DFADs (Moreno, Dagorn, Sancho, Garcia, & Itano, 2007) or at AFADs in the Philippines (Macusi, Abreo, & Babaran, 2017).

The Maldivian tuna fishery has traditionally been important. The tuna fishery has increased production with catches increasing from 30,000 tons in 1980 to 148,000 tons in 2018 (Ministry of Fisheries, Marine Resources and Agriculture / MoFMRA, 2019). Although this fishery uses AFADs since the 1980s, only one study investigated the behaviour of tuna at AFADs in the Maldives, through acoustic tagging (Govinden et al., 2013).

The objective of this study is to use LEK to improve our knowledge of tuna behaviour at AFADs in the Maldives, at the scale of the FAD array (including seasonal variations) and at the scale of individual AFADs.

1.1 The Maldivian tuna fishery and its management

The Maldives tuna fishery has existed for over a millennium (Mohamed Shiham Adam, 1999). Unlike many island nations, Maldivians depend more on pelagic fish resources than on coastal fish resources. Until tourism started to expand in the 1980s, coastal fish were never targeted on a commercial scale while tuna was being harvested for both local consumption and export. Tuna represents 98% of the total marine catches in the Maldives (MoFMRA, 2019).

Throughout the Maldives only hook and line (pole and line, handline, trolling and longline) fishing is practiced. About 75% of the tuna catch, mainly skipjack (*Katsuwonus pelamis*) and small yellowfin tuna (*Thunnus albacares*) (fork length <65cm), is caught using pole and line (Ahusan et al., 2018) while the rest is caught by handline and trolling. Although longline fishing for tuna occurred in the Maldives, it has been suspended since July 2019. Other gears such as purse seine, large gill nets or trawl nets were never used for fishing in the Maldives and are forbidden to ensure the sustainability of the stocks. At present there are no foreign fishing vessels or fleets operating in the Maldives EEZ. About half the total tuna catch landed in the Maldives (148,000 tons in 2018) is consumed locally.

The traditional livebait pole and line fishing technique has not changed much over the years, although fishers moved from small wooden sail boats (8 to 12 m in length) to large (25 to 30 m in length) mechanized vessels (Shiham et al., 2003). Within the pole and line tuna fishery there are two distinct categories: the artisanal fleet and the commercial fleet. The artisanal fleet comprises of small vessels (<20 m in length) with 8 to 12 crew members conducting day trips and usually selling their catches in the neighboring islands mainly for local consumption. These small vessels do not hold ice and cannot keep the fish fresh for more than a day. The commercial fleet comprises of large vessels (about 25 m to 30 m in length) with 20 to 30 crew members. These large vessels are designed to cope with rough sea conditions and can stay out at sea for several days. They have insulated holds and carry ice to keep the fish fresh. Most of these commercial pole and line vessels operate in the south of the Maldives but they can travel north to pursue better fishing grounds. There were 785 licensed local commercial tuna fishing vessels operating in the Maldives in 2018 (MoFMRA, 2019). These vessels are owned by families or individuals living in the Maldives. There are no company owned fleets in the Maldives. More than 17,500 active fishers (MoFMRA, 2019) work on these fishing vessels which operate within the Maldives EEZ.

In the Maldives skipjack and small yellowfin tuna are caught by targeting (i) free swimming schools (45.4%), (ii) logs or other drifting objects (11.3%), (which includes drifting fish aggregating devices (DFADs) deployed by purse seiners that pass through the Maldives EEZ), (iii) seamount associated schools (10.4%), and (iv) anchored fish aggregating devices (AFADs) (32.8%) (Miller et al., 2017). Studies showed that AFADs related catches contribute to nearly one third of all the tuna caught by pole and line in the Maldives (Miller et al., 2017). Traditionally, Maldivian tuna fishers have fished at logs or drifting objects associated schools for centuries and they refer to these objects that attract tuna as '*oivaali*' (a local name given to drifting objects). Thus, in the Maldives AFADs are called '*oivaali kandhufathi*'.

The AFAD fishery in the Maldives began in 1981(Naeem & Latheefa, 1994a), with experimental FADs deployed by the Ministry of Fisheries and Agriculture. Studies conducted by Anderson and Waheed suggested that the expansion of the AFADs network would help further increase tuna catches in the Maldives (Anderson & Waheed, 1990). With the success of this fishery, the number of AFADs deployed increased from an initial 10 (in late 1980s) to 55 AFADs in 2019. Currently the AFADs in the Maldives are deployed on average about 20 km from shore, at depths between 1000 to 2800 m (MoFMRA, 2019). All AFADs are constructed, deployed, maintained and managed by the government thus all pole and line vessels across the Maldives (both artisanal and commercial) have equal access to all the AFADs. During a single fishing trip one vessel may fish at several AFADs and there can be as many as 30 vessels fishing at one AFAD. Only pole and line fishing is permitted within a 3-miles radius of the AFADs. Outside the 3-miles radius of the AFADs, all permitted fishing gears in the Maldives can be used for fishing.

A particularity of the AFAD array in the Maldives is the low density of these devices, (i.e. the large distances between neighboring FADs) (Pérez et al., 2020). While other AFAD arrays in the world are characterized by short distances between FADs, (e.g. 2-14 km in Mauritius (Rodriguez-Tress et al., 2017) or 7-31 km around Oahu, Hawaii (Laurent Dagorn et al., 2007)) in the Maldives (with 55 AFADs – Figure 3.1) the distances between neighboring AFADs range from 25-48 km. FAD density (or inter-FAD distances) is typically a parameter that can be managed by governments or fishers. It can have impacts on fish behaviour and consequently on catches. It is therefore important to investigate the effects of this parameter on tuna behaviour through the comparison of fish behaviour in AFAD arrays differing by their inter-FAD distances (Pérez et al., 2020).

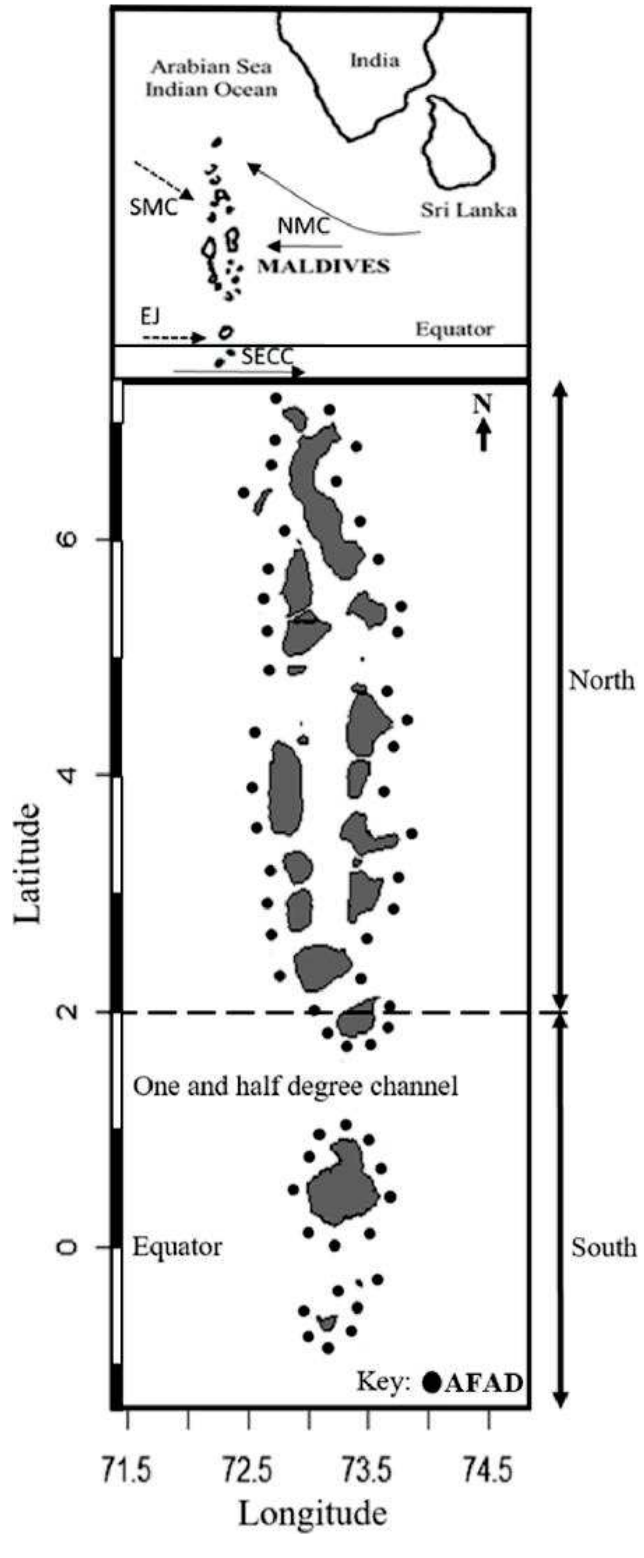

Figure 3.1: The study area, AFAD network outside Maldives atolls and the direction of monsoon related currents. (Dotted arrows indicate southwest monsoon currents and the continuous arrows indication northeast monsoon currents. NMC – northeast monsoon current, SECC – south equatorial counter current, SMC – southwest monsoon current, EJ – equatorial jet).

2 Materials and methods

2.1 Study site

The Maldives extends from about 7°N to 0.5°S stretching 822 km (Figure 3.1) and is 130 km at its widest. It is subjected to the seasonal monsoons (Anderson, 2005a; Schott & McCreary, 2001) – northeast monsoon is from December to March and the southwest monsoon is from May to October. From almost the northern tip of the Maldives up to about 2.5°N, the Maldives atolls are arranged in a double chain and below 2.5°N the atolls form a single chain and are separated with wide deep channels through which migratory fish such as tuna travel. In the south of the Maldives, the effect of the monsoon related currents is diminished and influenced by the equatorial systems (Anderson, 2005a; Schott & McCreary, 2001). More than two thirds of the yearly pole and line catch are landed by vessels operated in the south of the Maldives (Average pole and line catch for last 5 years: North (7° to 2°N) 16,000 t (SD±1000 t) and South (2°N to 1°S) 49,500 t (SD±6000 t) (MoFMRA, 2019)).

2.2 Fishers interviews

In the Maldivian tuna fishery, the captains or fishing masters (Locally called - *Keyolhu*) start their fishing career as a crew member on a pole and line vessel and work their way up to become a captain. They are responsible for making the decisions related to the fishing strategy – based on the information obtained from the surrounding environment by visual observations using binoculars and bird radar. In addition, the fishing strategy is also influenced by prior knowledge on the oceanographic conditions, weather and recent fishing activities in the area. Based on this information, the captain sets the course and steers the vessel. The captain is also responsible for taking appropriate decisions when approaching tuna schools and manoeuvring the vessel during fishing events. The deputy captain works closely with the captain and during his absence, makes all the necessary decisions.

To ensure the validity of LEK and the quality of information obtained, it is important to select participants who have the appropriate knowledge for the interviews (Moreno, Dagorn, Sancho, & Itano, 2007). The fishers for the interviews were selected based on their fishing experience and area of fishing. Hence captains (n=36), deputy captains (n=9) and crew members (n=9) from 36 vessels, who had a minimum of 8 years of experience on a licensed commercial pole and line vessel in the Maldives were selected. For this study, the Maldives archipelago was divided into north and south area at 2.0°N (Figure 3.1) based on the physiographic differences of the study site (Anderson, 2005a; Schott & McCreary, 2001) and fishing practices of the local tuna fishers. To limit potential geographical biases on the response of fishers from the north and the south of the archipelago, 34 fishers from the south and 20 fishers from the north were selected.

A questionnaire was developed to obtain fishers perceptions on tuna aggregations at AFADs. Questions were addressed through personal interviews conducted in the local language (Dhivehi) at commercial fish landing sites and fishers home ports (local islands) where their vessel is based. The questionnaire was not filled in the presence of the fishers since most fishers are reluctant to express freely when the interview becomes too formal. Interviews lasted about 30 minutes. All 54 fishers who contributed to the study provided verbal consent. No written consent was obtained since fishers were reluctant to sign any such documents. The study was approved by Marine Research Centre of the Ministry of Fisheries Marine Resources and Agriculture, Maldives.

To ensure consistency in the interpretations of the responses, all the interviews were conducted by the same individual (who had worked with tuna fishers for the last 10 years) in a friendly atmosphere and in an informal manner during 2017 and 2018. All fishers contributed enthusiastically to the interviews. For each question, the responses of the fishers were aggregated and converted into percentages. The questionnaire consisted of 11 questions and is included in Appendix 1.

2.3 Logbook data

All licensed pole and line fishing vessels report the mid-day position of the vessels during fishing operations and their daily catch in the logbook. The mid-day positions of the fishing vessels reported for the two monsoons, northeast monsoon (December to March) and southwest monsoon (May to October) were aggregated and used for calculating the percentage number of trips made during each monsoon season on the east and west side of the Maldives. All reported position between 70°E to 73°E were recorded as West and positions between 73.5°E to 76.5°E were recorded as East of the Maldives. Mid-day positions reported in the Central region 73°E to 73.5°E were not considered. April and November were considered as inter-monsoon periods and not included in the analysis. Logbook data of 2016 and 2017 were only used to assess the seasonal variation in fishing grounds reported by fishers.

2.4 Statistical analyses

Fishers responses on the months where tuna abundance is higher (question 1 of the questionnaire – see appendix) concerned five school types (AFAD, Log schools, DFAD, Free school, Seamount) and the two main target tuna species skipjack (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*). The responses were coded “1” for “yes” and “0” for “no” and were analysed by developing a data table with 12 columns (the months) and 540 rows (the answers of the 54 fishers for the 5 school types and the 2 species). Multidimensional data from LEK questionnaires are often analyzed using multivariate approaches such as nDMS and PERMANOVA (Azzurro, Moschella, & Maynou, 2011) Multiple Correspondence Analysis (Silvano & Begossi, 2012), and Principal Component Analysis (Taylor, Morrison, & Shears, 2011). Here, the table was subjected to a Principal Component Analysis on covariance matrix (centered PCA) in order to obtain an overview of the seasonality of tuna abundance, in relation with the species and the type of school but also with the origin and the position of the fishers. Four between-groups PCAs, a particular case of PCA with respect to instrumental variables (Lebreton JD, Sabatier R, Banco G, 1991) in which there is only a single factor as explanatory variable, were then performed to compute the ratio of variability explained by (i) the position of fishers (captains, deputy captains and crew members), (ii) the origin of fishers (north and south), (iii) the different types of schools and (iv) the species (skipjack and yellowfin). Monte-Carlo permutation tests (Romesburg, 1985) with 1000 random permutations were finally conducted to assess the significance level of the observed ratios in between-groups analyses. Chi-2 tests were used to compare the number of visits reported in the logbook between East and West of the Maldives. All statistical analyses were performed using R software (R Core Team R, 2019) with the ade4 package (Dray & Dufour, 2007).

3 Results

In general fishers were very cooperative in sharing their knowledge on the AFAD fishery and the behaviour of tuna around the AFADs. Several of them were keen to provide additional information that were not addressed in the questionnaire. All 54 fishers who took part in the interviews had no knowledge of the scientific publications related to tuna behaviour around FADs. The responses provided by the fishers at the scale of the AFAD array (questions 1 to 5, See Appendix 1) and at the scale of individual AFADs (6 to 11, See Appendix 1) are presented in Tables 1 and 2, respectively. Maldivian tuna fishers catch tuna from floating objects associated schools (AFADs, DFADs and logs), seamounts and free-swimming schools (Fig 2). AFADs are frequently used throughout the year by tuna fishers.

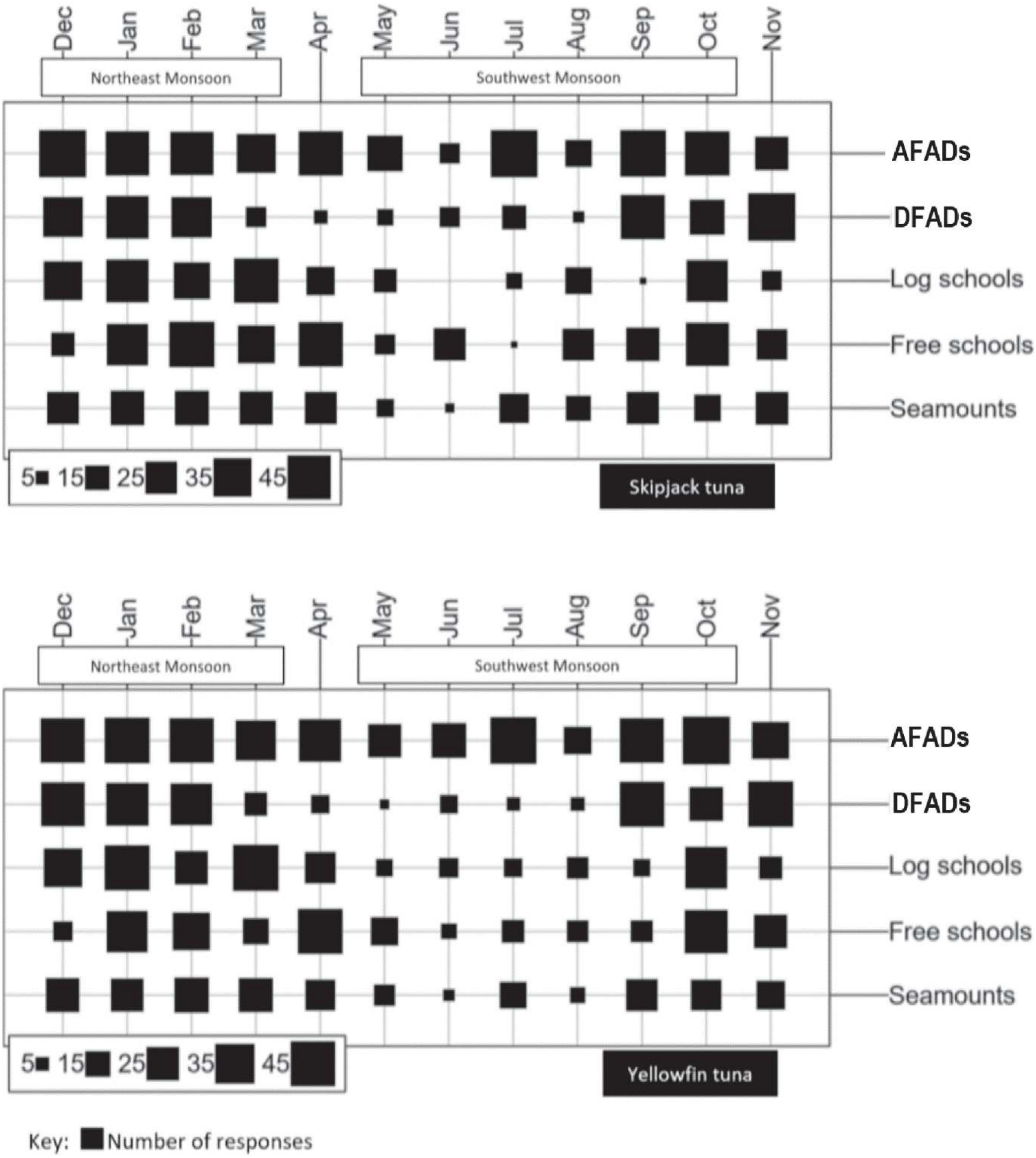

Figure 3.2: Fishers' response on the seasonal variation in abundance of two tuna species at five types of schools in the Maldives. April and November are inter-monsoon periods.

3.1 Tuna behaviour at the scale of the AFAD array

In the interviews, fishers globally agreed that there is a seasonal variation in abundance of tuna in the Maldives around the AFADs (Table 3.1). All fishers observed that during the northeast monsoon there are more tuna on the east side and during the southwest monsoon there are more tuna on the west side of the Maldives. The mid-day positions of pole and line fishing vessels obtained from logbooks during the northeast and southwest monsoons (Figure 3.3) showed a similar trend, with fishers tending to fish more on the east (45% - fishing events) than on the west (32% - fishing events) of the Maldives during the northeast monsoon (Contingency test, Chi-square = 95.368, df = 1, p-value<0.0001) and on the west (42% - fishing events) than on the east (39% - fishing events) of the Maldives during the southwest monsoon (Contingency test, Chi-square = 6.743, df = 1, p-value=0.009). The remaining vessels reported the central region as their mid-day position. When specifically asked about the tuna abundance throughout the year, it was highlighted that most skipjack and yellowfin were found around AFADs during the northeast monsoon.

Table 3.1: Fishers' response to seasonal variation and association behaviour of tuna at AFADs, at the scale of the AFAD array.

Questions	Percentage (%)	
There is seasonal variation in abundance/size of tuna around AFADs on the east and west of Maldives	Yes 94.4	No 5.6
There are more fish at AFADs on the east side of the Maldives during northeast monsoon	Yes 100	No 0.0
There are more fish at AFADs on the west side of the Maldives during southwest monsoon	Yes 100	No 0.0
When fish are present in the AFAD array – two adjacent AFADs do not have same amount of tuna	Yes 88.9	No 11.1
There are AFADs that always attract less tuna	Yes 79.6	No 20.4
There are AFADs that always attract more tuna	Yes 87.0	No 13.0

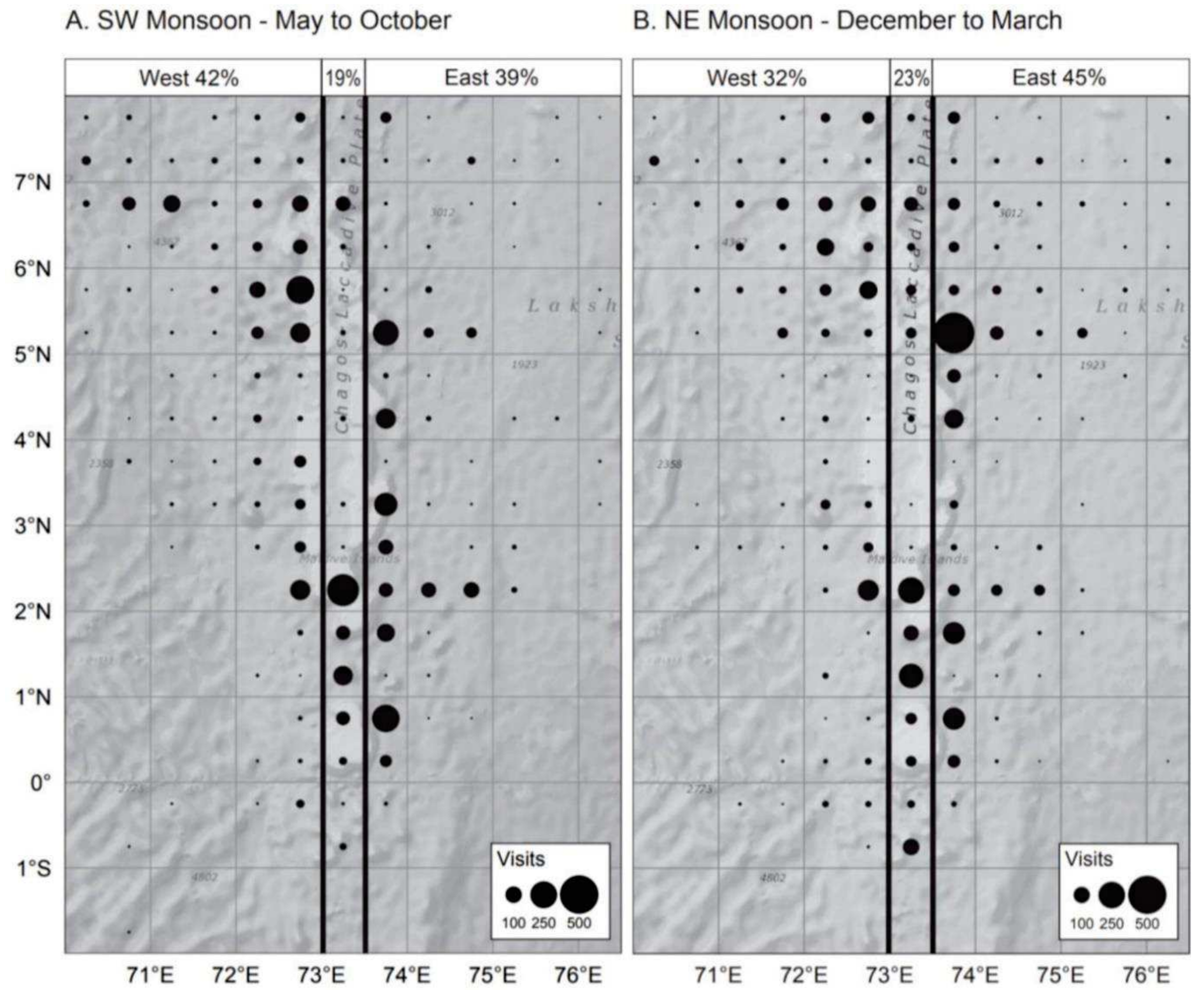

Figure 3.3: Mid-day position of pole-line-fishing vessels from logbook data for the southwest and the northeast monsoon periods for the west (70°E to 73°E), central (73°E to 73.5°E) and east (73.5°E to 76.5°E) regions.

The first two axes of the PCA (Figure 3.4) summarized respectively 20% and 14% of the information contained in the responses of the fishers about the seasonal variability of tuna abundance. The first axis opposed positive answers (all month projected on the left side) to negative answers (no month on the right side) (Figure 3.4A). As responses relative to AFADs were located mainly on the left side (Figure 3.4D), AFADs were considered by the fishers as globally attractive all-around the year. On the right side of axis 1 were the Log schools, Free schools and Seamounts, considered as globally less attracting fish. The second axis identified two groups of months: September and November to February on the upper side and the other months on the lower side (Figure 3.4A). The grouping of responses by school type (Figure 3.4D) allowed to conclude that, according to the fishers, more tunas were present around

DFADs during the northeast monsoon, while more tunas were present around AFADs towards the beginning and end of the southwest monsoon.

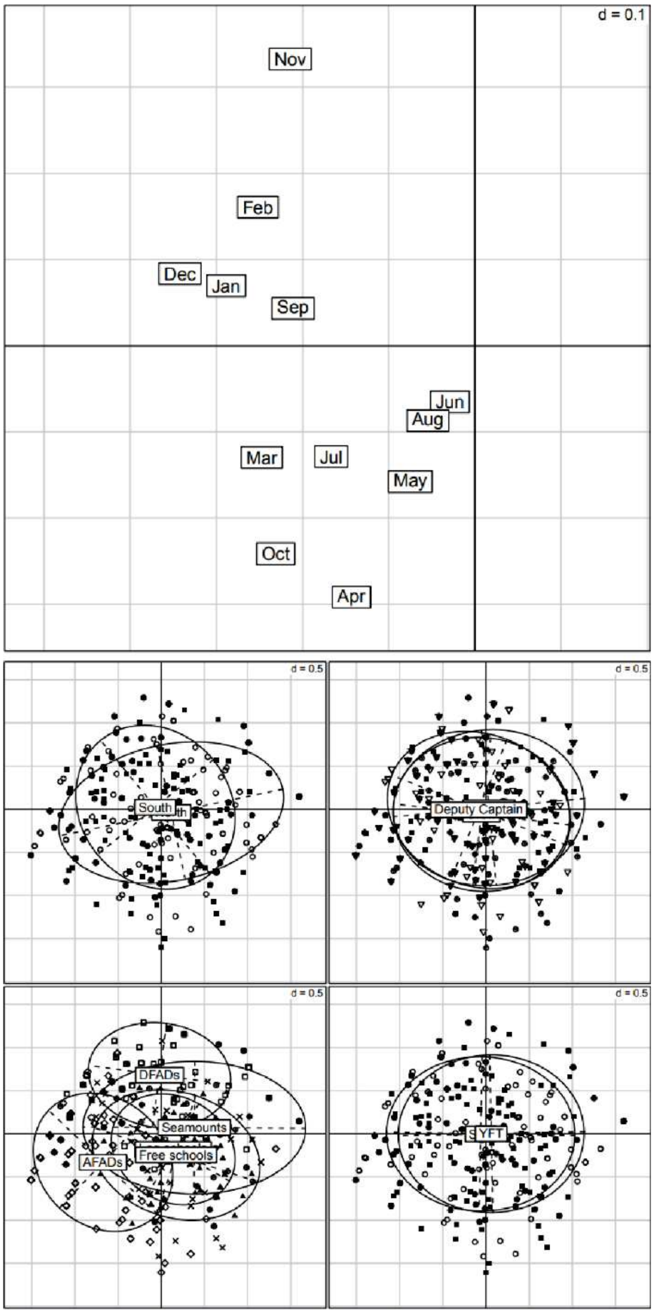

Figure 3.4: Results of the PCA on the monthly variability of tuna abundance. On the first two axes, representing respectively 20% and 14% of the total information, (A) projection of the 12 months and of the 540 rows grouped by: (B) Origin of the fisher - North (black squares), South (empty circles); (C) Position of the fisher - Captain (black square), Crew (empty triangles), Deputy Captain (crosses); (D) Type of school - AFADs (empty diamonds), DFADs (empty circles), Log Schools (black triangles), Free schools

(black squares), Seamounts (crosses) and (E): species SKJ (black squares), YFT (empty circles). The value of d in the top-right corner gives the scale of the grid.

Between-groups analyses, and the associated Monte-Carlo permutation tests confirmed that the abundance of fish over the months varied significantly according to the different types of schools (18.1% of explained variability – $p = 0.001$). However, there was no significant difference ($p = 0.133$) between skipjack and yellowfin tuna. The responses of the fishers according to their position (captain, deputy captain, and crew) did not differ ($p = 0.515$) while responses according to their origin (from the south and north of the Maldives) differed significantly ($p = 0.002$) but only explained 0.6% of the variability of the data table.

Almost 90% of the fishers said that when tuna are present in the AFADs array, two adjacent AFADs never had equal amounts of tuna (Table 3.1). Almost 80% of the fishers consider that there are AFADs that always attract less tuna than others, while 87% of the fishers consider that there are AFADs that always attract more tuna.

3.2 Tuna behaviour at individual AFADs

Most of the fishers (64.8%) believe that there are multiple schools of tuna at the AFADs while others (35.2%) think that there is one large mixed school (Table 3.2). All fishers observed that tuna move closer to the surface during sunrise and later afternoon, increasing their catchability at AFADs. Only a few fishers (11%) thought that there is a variation in the horizontal distance of tuna from AFADs over the day. Nearly half (40.7%) of the fishers interviewed thought that tuna stayed at the AFADs for 3 to 6 days while nearly one third (29.6%) believed that they stay less than 3 days. Few fishers (9.3%) suggested that aggregations can last for more than 10 days (but they specified that this occurs at very few AFADs during very good fishing periods). Most of the fishers (74%) suggested that tuna could be attracted to AFADs from up to 2 miles. A few (18%) suggested that it could extend to 5 miles. Some fishers (10%) suggested that this range could be area and season specific too.

Table 3.2: Fishers' responses related to formation of aggregation at AFADs, at the scale of individual AFADs.

Question	Percentage (%)	
There are multiple schools at AFADs and are segregated according to fish size and species	Yes	No
	64.8	35.2
Time of the day influence the behaviour of tuna at the AFADs	Yes	No
Horizontal distance from AFAD	11.1	88.9
Vertical distance from AFAD	100	0.0
Catchability	100	0.0
Number of days that tuna aggregation is retained at an AFAD		
Less than 3 days	29.6	
3 to 6 days	40.7	
7 to 10 days	20.4	
More than 10 days	9.3	
Distance fishers consider that the tuna is attracted to the AFADs		
0 to 2 miles	74.1	
0 to 5 miles	18.5	
> 5 miles	7.4	
Reasons for tuna to aggregate at AFADs?	Yes	No
Moderate current (1 to 4 knots)	83.3	16.7
Suitable temperature	37.0	63.0
Less turbid	20.4	79.6
Presence of prey	46.3	53.7
Presence of sharks	18.5	81.5
Attractants present	48.1	51.9
Sea state (average)	29.6	70.4
Reasons for tuna to leave the AFADs?	Yes	No
Strong current (>4 knots)	85.2	14.8
High sea surface temperature	40.7	59.3
Turbidity (very high)	13.0	87.0
Absence of prey	40.7	59.3
Presence of predators/mammals	29.6	70.4
Attractants absent	55.6	44.4
Storms / very rough sea condition	37.0	63.0
Large size of aggregations	24.1	75.9

Most of the fishers (83%) believed that current was the most important factor that drives tuna aggregations (Table 3.2). Moderate currents help to aggregate tuna at the AFADs. Almost half of the fishers (48%) thought that attractants (additional structures such as floats and ropes attached to the main buoy of the FAD) on the AFADs also contribute to the formation of aggregations while 46% fishers agreed that presence of prey (food for tuna) is also an important factor for the aggregations to form. About one-third (37%) of the fishers identified suitable sea surface temperature and average sea condition as other important factors. Some fishers believed that less turbid waters (20%) and sharks (18%) also play a role in the formation of aggregations.

Strong currents were identified by fishers (85%) as the most important factor that lead to the departure of tuna from AFADs (Table 2). Nearly half of the fishers (55.6%) thought that loss of attractants on the FADs could also result in the departure of tuna. High sea surface temperature and absence of prey were also identified as factors by 40.7% of fishers. Stormy conditions such as very rough seas (37%) and predators such as dolphins (29.6%) were believed to cause tuna to leave AFADs. Few fishers (13%) thought that high turbidity could also contributed to tuna departure.

4 Discussion

This study provides an insight into the spatio-temporal distribution and behaviour of tuna in the Maldives through the knowledge of tuna behaviour that fishers have observed during several years at sea. In the Maldives tuna fishers do not use sonars or echosounders for locating or observing tuna schools during their pole and line operation hence fisher's perceptions of tuna behaviour were completely based on what they had observed at sea during their fishing events. These experienced fishers, over the years, have accumulated vast amounts of knowledge on various aspects of tuna behaviour.

The seasonal variation in tuna abundance in the Maldives observed by the fishers (increase of abundance on the east of the Maldives during northeast monsoon and more tuna found on the west of the Maldives during southwest monsoon) and confirmed through logbook data, is similar to what was reported by Adam et al, (Anderson et al., 1998). In general, there are high catches observed during the northeast monsoon (lasts for 4 months) than in southwest monsoon (lasts for 6 months). Over the last five years (2014 to 2018) MoFMRA catch statistics showed that the average catches during northeast monsoon (during a 4 months period) was 50,000±2000 t while in the southwest monsoon (during a 6 months period) it was at

54,000±3000 t. This could be due to severe weather conditions experienced during the southwest monsoon, making it difficult to fish. Fishers encounter more natural floating objects (log) associated schools during the northeast monsoon (Fig 2) and believe that tuna associated to floating objects and free-swimming schools of tuna move towards the Maldives with the monsoon currents. Similar observations were made by Adam et al, (Anderson et al., 1998), with a pattern that could correspond to tuna entering the Maldives from the north (on the east side) at the beginning of the northeast monsoon and tuna entering from the south (on the west side) towards the beginning of the southwest monsoon.

Almost all the fishers agreed that they have never observed equal amounts of tuna at two adjacent AFADs but a few said that, when tuna was very abundant around the atolls they had, on few occasions, seen similar aggregations at two adjacent AFADs. The origin of this question relates to the fact that for social species (e.g. tuna), the competition of two attracting devices could lead to one of the devices aggregating most of the local population (Sempo, Dagorn, Robert, & Deneubourg, 2013). Robert et al., 2013 designed an experiment with AFADs in the Seychelles to test this hypothesis on tuna and showed that tuna generally aggregate to one of the two close FADs. In their experiment, however, FADs were only 5 km apart. In the Maldives, two adjacent FADs are always more than 25 km. According to fishers, although FADs are quite far from each other, the selection of only one FAD seems to be a common observation. This suggests that even when AFADs are distant by more than 25 km, the competition between two adjacent devices could occur. This hypothesis must be investigated, in particular through new experiments, using echosounder buoys (Jon Lopez, Moreno, Ibaibarriaga, & Dagorn, 2017; Robert et al., 2013) attached to AFADs. Such a protocol would allow to investigate whether adjacent FADs can simultaneously host large tuna aggregations.

Echosounder buoys attached to AFADs could also contribute to investigate the information provided by fishers that some FADs always attract more (or less) tuna than others. It is difficult to consider that design or location of FADs could explain why some FADs attract more tuna than others, as all AFADs in the Maldives are built following the same design and are anchored very deep (> 1000 m). By monitoring FAD aggregations through echosounder buoys over long periods (several weeks and months), it would be possible to further understand this information provided by fishers.

Most fishers (64.8%) believe that multiple schools of tuna, segregated by species and size, form the aggregation around AFADs. These fishers observed that during fishing operations around AFADs, when several vessels fish simultaneously, some vessels caught only small size fish while other vessel caught bigger fish. The same pattern was reported by Moreno et al, where skippers of purse seines also considered that several tuna schools form an aggregation around a DFAD, segregated by species and sizes (Moreno, Dagorn, Sancho, & Itano, 2007). Macusi et al, also reported a similar pattern for tuna at AFADs in the Philippines (Macusi et al., 2017). Some fishers (35.2%), however, believe that there is only one large school where different species and sizes mix. It is possible that both situations occur at AFADs, depending on the local biomass and environmental/ oceanographic conditions.

All fishers observed that fish move closer to the surface during sunrise and late afternoon, increasing their catchability at the AFADs during these periods. This diel behaviour, with tuna swimming deeper during the day and shallower during the night, is well known for pelagic species, and has been observed for tuna in electronic tagging studies (F. G. Forget et al., 2015; Macusi et al., 2017; Schaefer & Fuller, 2013). This matches the usual upward movement of the Deep Scattering Layer (DSL) at night (see Dagorn et al, (L. Dagorn, Bach, & Josse, 2000)). A few fishers (11.1%) also thought there was some variation in the horizontal positioning of tuna at AFADs during the day. Schaefer and Fuller during their ultrasonic telemetry experiments at DFADs in 2013 observed that skipjack schools break into small sub-schools and tend to move away from the FAD but return to it after few hours (Schaefer & Fuller, 2013). However, it is possible that the fishers in the Maldives, that fish at the AFADs only during the daytime, do not experience such horizontal movements.

The time tuna aggregations spend at FADs is considered as a key parameter to characterize their associative behaviour and one of the elements to derive novel indices of abundance. Capello et al, developed a new method for estimating the local abundance of tropical tuna that uses the characteristics of the FAD associative behaviour of tuna, the time fish spend at FADs being one of the parameters used in the model (Capello et al., 2016). It is worthy to note the differences between the residency times of individual fish and those of fish aggregations. The residency of individuals and aggregations at FADs are obviously linked, but could be different, as aggregations could result from the turn-over of individuals: some fish can join the aggregation while others leave and the aggregation can be maintained. Two methods exist to measure the time fish aggregations stay at FADs: LEK and echosounder buoys (see Baidai et al, (Baidai, Dagorn, Amande, Gaertner, & Capello, 2020)). Maldivian fishers provided a very wide range of times tuna aggregations stay at AFADs, suggesting that fish can spend very little time at FADs (30% of fishers considered that tuna stay less than 3 days at AFADs), or can stay more than 10 days (9% of answers), with all intermediate situations. In the study by Macusi et al, in the Philippines, fishers also provided a wide range of times (from one week to more than one month) for tunas to stay around FADs(Macusi et al., 2017). Nearly half of the fishers interviewed believed that tuna stay at AFADs for 2 weeks, which is considerably longer than what is reported by Maldivian fishers. Recently, estimated time series of presence/absence of tunas at DFADs using echosounder buoys they found that in the Indian Ocean, DFADs were continuously occupied by tuna aggregations for 6 days in average (Baidai et al., 2020). These values are of the same order than those provided by Maldivian fishers. Several acoustic tagging studies were designed to document the time individual tuna spend associated with AFADs and DFADs, including a study in the Maldives, which could directly be compared to our study.

In the Maldives, individual tuna were observed to stay in average less than a day or 3 to 4 days associated to FADs, depending on the period and the species, but the maximum observed residency was 12.8 days (Govinden et al., 2013). Information provided by fishers are coherent with these field results. Similar studies conducted in other AFAD arrays showed average FAD residency times from 2 to 10 days, depending on the species and area (Robert et al., 2013; Rodriguez-Tress et al., 2017). Pérez et al, compared FAD residency times of tuna between AFAD arrays differing by their inter-FAD distances (or FAD densities) (Pérez et al., 2020). They found that the durations of associations of tuna at AFADs in the Maldives were shorter than those measured at AFADs in Mauritius and Hawaii. They concluded that when inter-FAD distances decrease, fish spend more time associated with FADs, suggesting that this could be a result of social behaviour and/or prey availability. As Maldivian fishers regularly visit AFADs, we believe that they could note and report more precise information on the time when AFADs are occupied by tuna (and vice versa, when they are empty). By involving fishers in the collection of such new information, we could obtain time series that could be compared with data from echosounder buoys attached to AFADs in order to evaluate the effectiveness of such a protocol. This would have both advantages: better involvement of local fishers into science, and then management, and cheaper collection of data on the behaviour of tuna at AFADs (as compared to electronic tagging or echosounder buoys).

Most of the fishers (74.1%) suggested that tuna could be attracted to AFADs as from 2 miles (about 3.7 km) while some fishers suggested that the attraction distance varies depending on the area and the season. Skippers of tuna purse seiners considered that tuna could be attracted towards DFADs from 0 – 5 nautical miles (0 – 9 km) (Moreno, Dagorn, Sancho, Garcia, et al., 2007; Moreno, Dagorn, Sancho, & Itano, 2007). Data collected from active acoustic tracking of tuna at AFADs in the Indian and Pacific Oceans (Brill et al., 1999; L. Dagorn et al., 2000; Girard et al., 2004; Holland, Brill, & Chang, 1990) suggest that the orientation distances ranged from 4 to 19 km, with a mode at about 10 km. This was similar to the estimates of the skippers of the purse seiners but the attraction distance suggested by Maldivian fishers are lower. The distance proposed by the Maldivian fishers could be influenced by the visible sighting distance of the AFAD buoy (about two miles radius) – beyond which the buoy is often not visible to eyes. Active tracking of tuna at AFADs in the Maldives would document the attraction distance more precisely, but it is noteworthy that all studies, including ours, tend to suggest that tuna could be attracted from a few kilometers to AFADs.

Most fishers (98.3%) believed that more than a single factor contributes towards the formation and dissolution of tuna aggregations at AFADs. A large majority agreed that the currents had the highest impact on the aggregations at AFADs. Skippers of large tropical tuna purse seiners also reported that strong currents, changes in temperature and rough sea conditions can have a strong impact on the tuna aggregations at FADs (Moreno, Dagorn, Sancho, & Itano, 2007). Macusi et al, also identified changes in sea currents as one of the main reasons for tuna departure from AFADs in the Philippines (Macusi et al., 2017). Several other studies have also suggested that the residency of tuna at FADs, and their departure, could be influenced by local oceanographic conditions (Brill et al., 1999; Cayré & Marsac, 1993; Schaefer & Fuller, 2010).

Some fishers (46.3%) believed that the presence of prey help form aggregations while (40.7%) believed absence of prey cause the aggregations to leave the FAD. These fishers believed that tuna feed on various prey items in the vicinity of the AFADs and the abundance of tuna is related to local prey abundance. Several studies have suggested that prey availability around the FADs affects the duration of the aggregations (Graham, Grubbs, Holland, & Popp, 2007; Musyl et al., 2003; Ohta & Kakuma, 2005). In the pole and line tuna fishery of the Maldives, fishers almost daily chum large quantities of livebait at the AFADs and some fishers suggested that this could encourage the tuna to remain at the AFADs longer but CRTs in the

Maldives are no longer than in other countries. Most fishers (75.9%) did not believe that large school size leads to tuna departures from the AFADs. This is also similar to the observations made by the purse seine fishers (Moreno, Dagorn, Sancho, Garcia, et al., 2007).

Some fishers (48.1%) also suggested that large predators such as sharks, dolphins and toothed whales can affect the behaviour of tuna. Fishers (18.5%) consider that sharks associated with AFADs could somehow help maintain tuna aggregations at AFADs. This striking information has never been documented in any other scientific publications. Forget et al, and Filmalter et al, using acoustic tracking, showed that silky sharks made excursions away from a DFAD, being closely associated with a school of tuna (Filmalter, Cowley, Forget, & Dagorn, 2015; F. G. Forget et al., 2015). While these studies indicate that silky sharks and tunas tend to exhibit similar associative patterns, they do not allow to investigate whether sharks play a role in the associative behaviour of tuna to floating objects. Fishers (29.6%) also observed that continuous chasing of tuna by predators negatively affected catchability of tuna. The same effect of marine mammals on the departure of tuna from FADs was reported both by fishers fishing on AFADs in the Philippines (Macusi et al., 2017) and by skippers of purse seiners fishing on DFADs (Moreno, Dagorn, Sancho, Garcia, et al., 2007). Generally, these reports tend to suggest that the presence of predatory mammals has a negative impact on the residency of tuna at FADs.

Maldivian fishers believe that attractants such as additional ropes, floats and netting on AFADs also influence the tuna aggregations. The AFADs deployed in the Maldives have a set of small floats weaved together as an attractant. Sometimes fishers attach pieces of thick ropes or occasionally, pieces of nets that they have recovered from DFADs to serve as attractants. Tuna fishers regularly check on the attractants attached to the AFADs and if the attractants are missing from an AFAD, they inform MoFMRA to attach new attractants. They believe these attractants provide some form of shelter to the small fish that help to form tuna aggregations. However, studies have investigated the diet of tuna associated with floating objects and concluded that tuna do not feed extensively on associated fauna (Ménard et al., 2000). Small fish associated to AFADs could therefore play a role in the association of tuna through other mechanisms, such as production of signals (e.g. sounds) which could help tuna locate FADs.

5 Conclusion

With an increase in demand for tuna, both locally and internationally, it is important to ensure the sustainability of the fishery. The sustainability of the fishery depends on the status of the fish resources, the health of the ecosystem, the livelihoods of fishers. Assessing fish resources and the health of the ecosystem requires a good understanding of the marine ecosystem, including the behaviour of tuna. For instance, Capello et al, developed a method to derive indices of abundance from characteristics of the FAD associative behaviour of tuna (Capello et al., 2016). In a more general way, the behaviour of fish, including seasonal variations in the abundance, along with the biology of fish and fishery statistics (e.g., catch and effort), are necessary for assessing the health of the resources. Knowledge on the behaviour of fish is commonly collected through scientific methods (e.g., tagging, sonars, etc.) but fishers, through other methods, also developed knowledge on fish behaviour. Scientists should combine information from scientific methods as well as from LEK. Another major output of this study corresponds to the involvement of local fishers in science and subsequently in the management of the fishery. We recommend to regularly conduct LEK studies (e.g. every year), instead of punctual and ephemeral ones, for two main reasons. First, it provides a regular flow of information allowing for time series, always useful to monitor and understand the evolution of a system. Of course, questions should be adapted to knowledge that can change every year. Second, it keeps fishers involved in science, realizing that their knowledge is valuable and used by scientists. This appears to be important to close the gap between fishers and scientists, which can also contribute to close the gap between fishers and managers.

Appendix

Local Ecological Knowledge – Fisher interview questionnaire

1. During which season (monsoon) are there more fish (any size) around different types of schools?

Species	SKIPJACK TUNA												YELLOWFIN TUNA											
Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
AFAD																								
Seamount																								
Free school																								
DFAD																								
Log school																								

2. Is there any variation in abundance of fish around AFADs on the east and west of Maldives? (Are there more fish on the east during northeast monsoon? Are there more fish on the west during southwest monsoon?)
3. Are there any AFADs that generally attract less fish?
4. Are there any AFADs that generally attract more fish?
5. When AFADs are close by (adjacent) do more fish appear on one AFAD than other or are they equal?
6. When a FAD aggregates fish how many days is the aggregation around?

   Options provided: ***<3days, 3 to 6 days, 7 to 10 days, >10days***

7. Which are the most important factors that help the formation of fish aggregation at AFADs?

   Options provided: ***current, temperature, turbidity, presence of prey, attractants attached, sea state.***

8. Which are the most important factors that explains why fish leaves the AFADs?

   Options provided: ***current, temperature, turbidity, absence of prey, absence of attractants, stormy seas, presence of large predators, large size of the aggregations.***

9. What is the distance that you consider that the fish is still associated to the AFAD?

   Options provided: ***0 to 2 miles, 0 to 5 miles, >5 miles***

10. Does time of the day influence the behavior of tuna at the AFADs?

    Options provided: horizontal distance from AFAD, vertical distance from AFAD and catchability

11. Do you think there are multiple schools of fish at the AFADs?

Chapter 4

An original in situ experiment to test a hypothesis on tuna movements within a FAD array

Manuscript for publication

To be submitted to Journal of Experimental Marine Biology and Ecology

A Riyaz Jauharee[1,2*], Fabien Forget[2], Manuela Capello[2], M Shiham Adam[3], Laurent Dagorn[2]

[1]Maldives Marine Research Institute, Ministry of Fisheries, Marine Resources and Agriculture, Male, Maldives.

[2]MARBEC, University of Montpellier, CNRS, Ifremer, IRD, Sète, France

[3]International Pole and Line Foundation, 1 London Street, Reading, RG1 4QW, United Kingdom.

Abstract

In order to test the hypothesis of a preferential direction in the movements of tuna in the Maldivian anchored FAD array, 65 skipjack and 57 yellowfin tuna were tagged with acoustic transmitters. Two tagging campaigns in 2017 and 2018 within a subsection of the array consisting of 21 AFADs equipped with acoustic receivers, were carried out. Only three yellowfin tuna (5.2%) and one skipjack tuna (1.5%) were observed to move from one FAD to another. These four fish were tagged together at the same FAD during the same tagging campaign, while no fish tagged at the other FADs and tagging campaigns moved between FADs. Despite being tagged together, the fish that moved between the AFADs were detected at different FADs located in different directions, suggesting that they did not have a specific preference in the direction of movement. The mean continuous residence time at FADs for all tagged skipjack and yellowfin tuna were 2.03±2.93 days and 4.42±6.72 days, respectively. The few observed inter-AFAD movements of tuna suggest that the AFAD array in the Maldives, with its large inter-AFAD distances, does not act as a network but rather as individual AFADs that locally attract tuna. In contrast to other denser AFAD arrays in the world, it appears that large distances between FADs minimize any possible FAD effect on tuna movements.

1 Introduction

Large schools of tuna are attracted to various types of floating objects in the marine environment (Castro et, al., 2002; Kingsford, 1993). These floating objects can be natural or man-made such as anchored fish aggregating devices (AFADs). In the Indian Ocean, several countries including the Maldives use AFADs for aggregating tuna for fishing. The Maldives have one of the most extended AFAD arrays in the world (Govinden et al., 2013) stretching over 900 km in the middle of the Indian Ocean. All the AFADs in the Maldives are deployed by the government who takes the full responsibility of maintaining this relatively low-density array of AFADs. Other AFAD arrays are usually characterized by shorter distances between FADs, e.g. 2-14 km in Mauritius (Rodriguez-Tress et al., 2017) or 7-31 km around Oahu, Hawaii (Laurent Dagorn et al., 2007), while in the Maldives (with 55 AFADs), distances between neighbouring AFADs range from 25-48 km.

Govinden et al., (2013) investigated the behaviour of tuna at AFADs in the Maldivian array through acoustic telemetry. In their study, skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares)* tuna were tagged at two AFADs in the center of a set of eight AFADs aligned on a north-south axis, all equipped with acoustic receivers (Figure 4.1). No inter-AFAD movement was observed within the equipped AFAD array, neither to the north nor to the south of the AFADs of tagging. The authors hypothesized that the absence of observed movements between equipped AFADs could be due to the large inter-FAD distances. If tuna had moved north-south or south-north, however, some movements between AFADs should have been observed, even for FADs distant by a few tens of kilometres. Another hypothesis could be that in this region, tuna have a general west-east (or east-west) movement. However, since the AFADs on the west of the study area were not equipped, and no AFADs exist on the east, it was not possible to verify any east-west or west-east movement.

The objective of this study was to test the hypothesis that tuna in the Maldives adopt a general east-west or west-east movement, which would help interpreting results from Govinden et al. (2013), including the possible role of the inter-FAD distances. Additionally, the study estimates the durations of individuals' association with FADs, with the aim of comparing them with the durations measured in the Maldives previously (Govinden et al., 2013) and also in other FAD arrays with lower inter-FAD distances (see (Pérez et al., 2020) for a summary of data from other studies).

2 Materials and methods

2.1 Study site

The Maldives extends from 7ºN to 1ºS in the central Indian Ocean (Figure 4.1). From about 6ºN to 2.5ºN, the Maldives atolls are formed in a double chain and below 2ºN, the atolls form a single chain and are separated with wide deep channels such as the equatorial channel and the one-and-half degree channel through which pelagic fish such as tuna could easily swim through. Across the Maldives there is an array of 55 AFADs deployed about 20 km from the outer edge of the atolls moored at depths ranging from 1000 m to 2800 m.

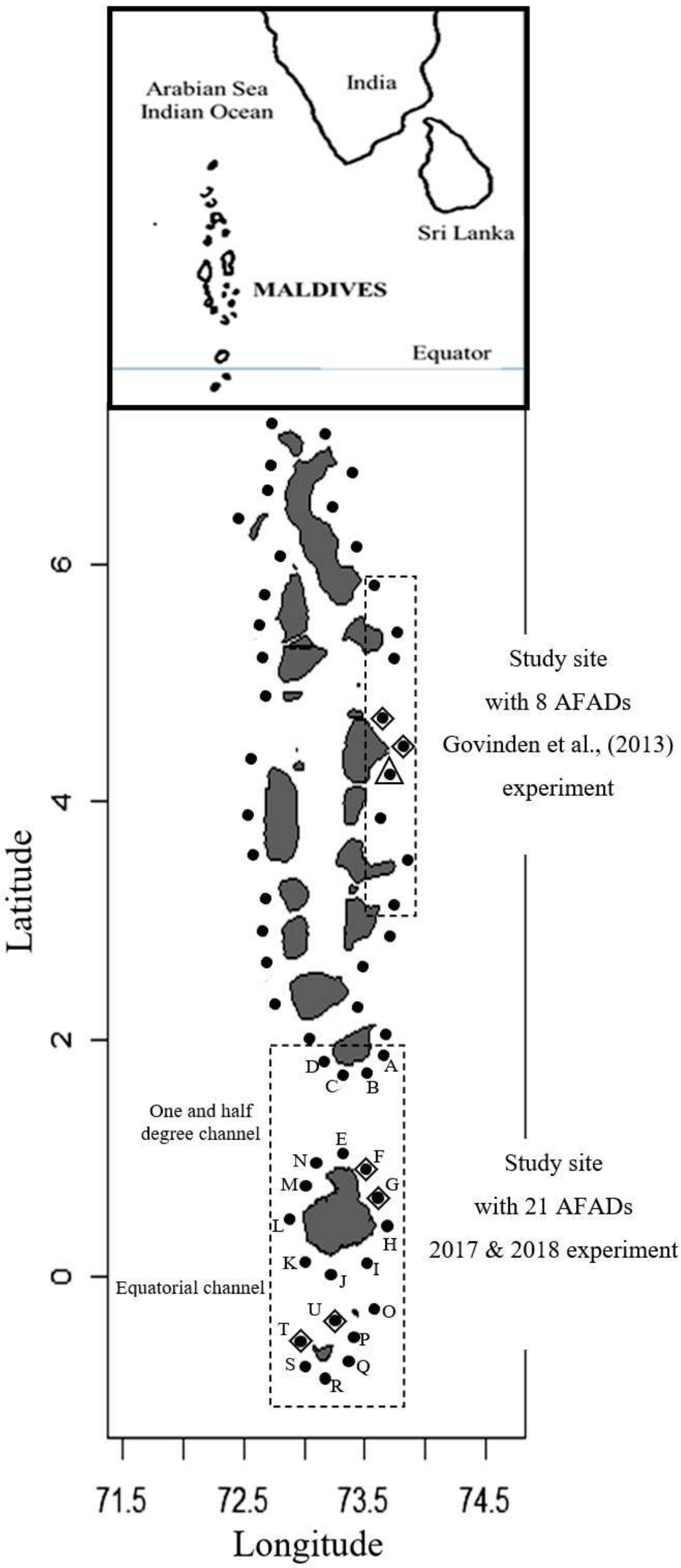

Figure 4.1: Current anchored FAD array in the Maldives with location of this study site and of Govinden et al. (2013) study site. (●AFADs,◇Acoustic tagging AFADs, △AFAD deployed in 2019 that was not present in the site during 2009 study).

The study site for the Govinden et al. (2013) study was in the north-east part of the archipelago, with all equipped AFADs aligned on a north-south axis (Figure 4.1). Our study site was in the south of the Maldives, between 2°N and 1°S and 72.5°E and 74.0°E (Figure 4.1), in order to work in a sub-array with a more homogeneous spatial distribution of AFADs. In this site there were 21 AFADs with distances between neighbouring AFADs of 27-35 km while in the Govinden et al. (2013) study site (with 8 AFADs) the neighbouring AFADs were 38-60 km. In 2017 acoustic tagging was strategically conducted at two AFADs (F and G, see Figure 4.1) on the east side of the array and in 2018 at four FADs (F, G, T and U, see Figure 4.1) both on the east and west side of the array. This spatial distribution of AFADs in our study site therefore leads to more AFADs located within a given distance from each tagging AFAD (Figure 4.2) or, in other words, a denser sub-array as compared to the Govinden et al. (2013) study.

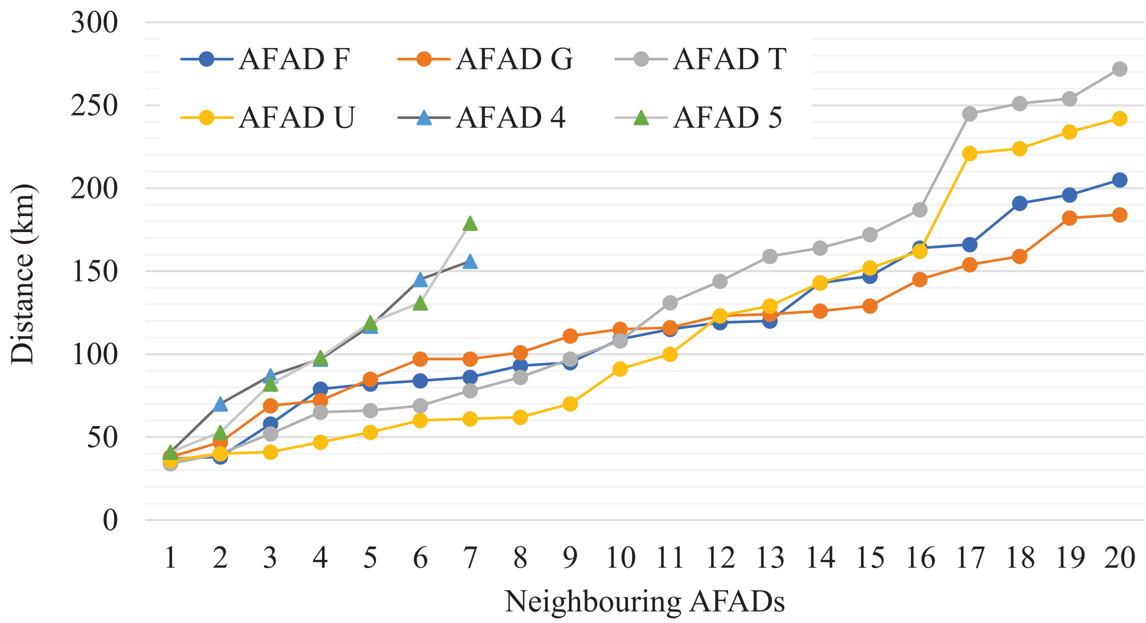

Figure 4.2: Inter-AFAD distances between the tagging FADs and neighbouring FADs. (2017/2018 study – AFADs F, G, T and U; 2009 study – AFADs 4 and 5).

All 21 AFADs of our study site were instrumented with acoustic receivers (VR2W, Vemco, Halifax, Canada). The acoustic receivers were fixed to the main mooring ropes of the AFADs at depths between 12 m and 15 m. Two plastic cable ties helped to position the receiver with the hydrophone pointing downwards. In 2017, all the receivers stayed attached to the FADs from 15 February till 17 May (98 days). In 2018, the receivers were deployed at the AFADs between 15 February and the 30 September (227 days), well into the southwest monsoon.

2.2 Acoustic tagging

Like Govinden et al. (2013), this study focused on the two major commercial tuna species (skipjack tuna – *Katsuwonus pelamis*, and yellowfin tuna – *Thunnus albacares*) found at AFADs in the Maldives. Tagging was conducted on a pole and line fishing vessel. Fish caught by fishers were gently placed by scientists on a V-shaped tagging table positioned at the back of the boat. A wet cloth covered the eyes while a hose with flowing saltwater was placed in the mouth of the fish to ensure the gills were ventilated. Fish were equipped with internal acoustic transmitters (Vemco V13-1L-R64K, 69 kHz, 50−130 s delay, estimated battery life 878 days). The transmitter was placed inside the peritoneal cavity of the fish by making an incision using a sharp scalpel in the abdominal musculature about 2 to 3 cm from the anus. The opening was closed by two sutures made using monofilament nylon. The average size of tagged fish was 41.9 ± 6.3 cm and 43.5 ± 7.0 cm for skipjack and yellowfin tuna, respectively. A total of 65 skipjack and 57 yellowfin tuna were tagged in through 2017 and 2018 (respectively at 2 and 4 FADs) constituting 6 different replicates. A tagging replicate is defined as fish tagged the same day at the same FAD (Table 4.1).

Table 4.1: Acoustic tagging replicates with number of tagged skipjack and yellowfin tuna.

AFAD	Tagging replicate	Number of SKJ – YFT tagged
F	9 Mar – 16 Mar 2017 15 Mar – 17 Mar 2018	5 – 8 8 – 14
G	11 Mar – 16 Mar 2017 12 Mar 2018	14 – 12 11 – 9
T	18 Mar – 19 Mar 2018	17 – 4
U	18 Mar 2018	10 – 10

2.3 Data analysis

The continuous residence time (CRT) of individual tuna at AFADs was calculated based on the definition provided by Ohta and Kakuma (2005), that is "the duration in which a tagged tuna was continuously monitored without day-scale (> 24 hours) absence". A fish was considered to be present at a FAD if it was detected at least three times at the FAD, in order to avoid any false detection. The continuous absence time (CAT) was calculated as the time between two AFAD associations (Capello et al., 2016; Rodriguez-Tress et al., 2017). The overall directions of movements between AFADs were estimated by calculating the angle relative to the north of the direct line between the AFAD of departure and the AFAD of arrival.

Hence if the direction is between >315 and ≤45 it was considered north, >45 and ≤135 it was considered east, >135 and ≤225 it was considered south and >225 and ≤315 it was considered west. The speed of the tuna was calculated by dividing the shortest distance between the two AFADs by the time it took to travel from one FAD to the other.

Wilcoxon signed ranked test was used to compare the CRTs of the skipjack and yellowfin tuna tagged at the four FADs during the 6 tagging replicates. The same test was also applied for comparing CRTs recorded within the two tagging campaigns (2017 and 2018) for each species and to run a comparison between species for all CRTs. The null hypothesis was rejected at the 0.05 threshold, and the Bonferroni correction was applied to account for multiple pairwise tests. All statistical analysis were performed using R software (R Core Team R, 2019)

3 Results

3.1 Tuna movements between AFADs

Only four individuals (3.3% of all tuna tagged) of the 122 tuna tagged were detected at an instrumented AFAD other than where they were released: three yellowfin (5.2% of all tagged yellowfin tuna) and one skipjack tuna (1.5% of all tagged skipjack tuna). In total, these fish exhibited seven movements, whose characteristics are detailed in Table 4.2.

Table 4.2: AFADs of departure/arrival, direction of movement, distance, CAT and estimated speed for the four tuna that moved between AFADs.

Tuna	AFAD		Direction		Distance (km)	CAT (days)	Speed (km/h)
	Left	Arrived					
YFT (FL 51 cm)	G	F	335°	North	38	2.3	0.69
	F	E	300°	West	37	2.5	0.62
YFT (FL 52 cm)	G	N	270°	West	85	13	0.27
	N	E	80°	East	27.5	8	0.14
	E	G	138°	South	72	134	0.02
YFT (FL 54 cm)	G	O	172°	South	101	165	0.03
SKJ (FL 38 cm)	G	H	188°	South	47	1.27	1.54

Table 4.3: Acoustically-tagged tuna released during 6 tagging events and inter-AFAD movements observed.

Released AFAD	Tagging events	Number of SKJ – YFT tagged	Number of fish that moved between AFADs SKJ – YFT	Number of AFAD movements SKJ – YFT	Number of neighbouring AFADs within 100 km
F	9 to 16 March 2017	5 – 8	0 – 0	0 – 0	9
G	11 to 16 March 2017	14 – 12	0 – 0	0 – 0	7
F	15 to 17 March 2018	8 – 14	0 – 0	0 – 0	9
G	12 March 2018	11 – 9	1 – 3	1 – 6	7
T	18 and 19 March 2018	17 – 4	0 – 0	0 – 0	9
U	18 March 2018	10 – 10	0 – 0	0 – 0	10

It is noteworthy that these four fish were tagged during the same tagging replicate at AFAD G in 2018, corresponding to 20% of fish (all species considered) tagged during this replicate exhibiting movements between AFADs. No fish from any of the other five tagging replicates was observed at any other AFAD than the tagging AFADs. Considering only the seven observed between-AFAD movements, four corresponded to a north-south axis while three were on a east-west axis (Figure 4.3 and Table 4.2). One yellowfin (FL = 51cm) travelled north from G to F and then to west from F to E (Figure 4.3). Another yellowfin (FL = 52cm) travelled west from G to N and then to east from N to E. Then it moved south from E to G. The third yellowfin (FL = 54cm) moved south from G to O. The skipjack swam from AFAD G to AFAD H in the south.

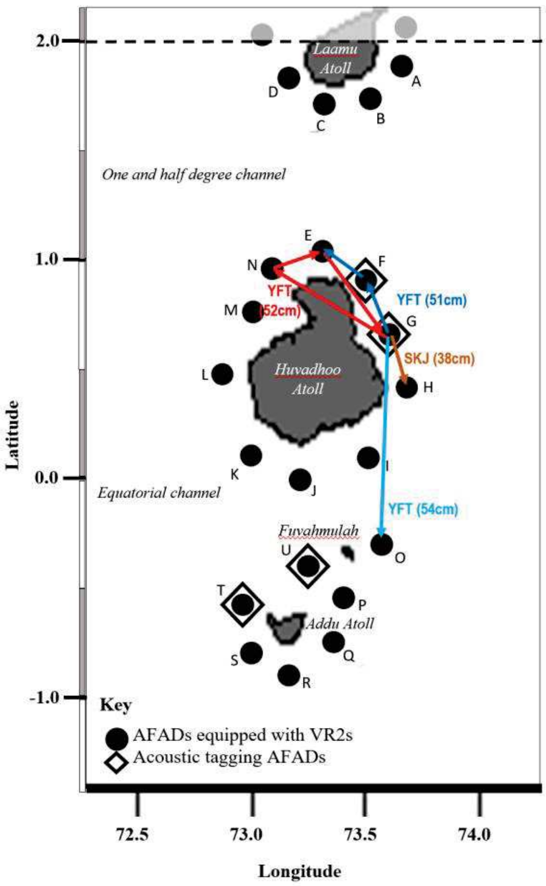

Figure 4.3: Tuna movements between AFADs in the instrumented array. Solid circles denote FADs, diamonds denote AFADs where tagging was conducted. The arrows denote the movements and direction displayed by tagged individuals which displayed a movement between different AFADs. YFT: yellowfin tuna, SKJ: skipjack tuna

For each of these four fish, Figure 4.4 details the residence times (CRT) at FADs and the absence times (CAT) between two associations. Two yellowfin tuna (52 cm and 54 cm) showed exceptionally long CATs (133.84 days and 168.28 days respectively).

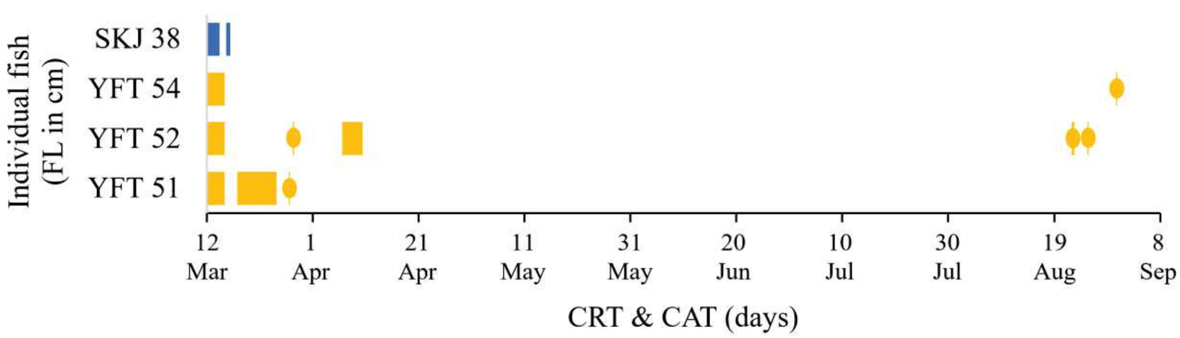

Figure 4.4: CRTs at each visited AFAD by the four tuna that were detected at an AFAD other than the one where they were tagged and released. (CRT < 1 day ⬮, yellowfin tuna ■, skipjack tuna ■).

3.2 Continuous residence times

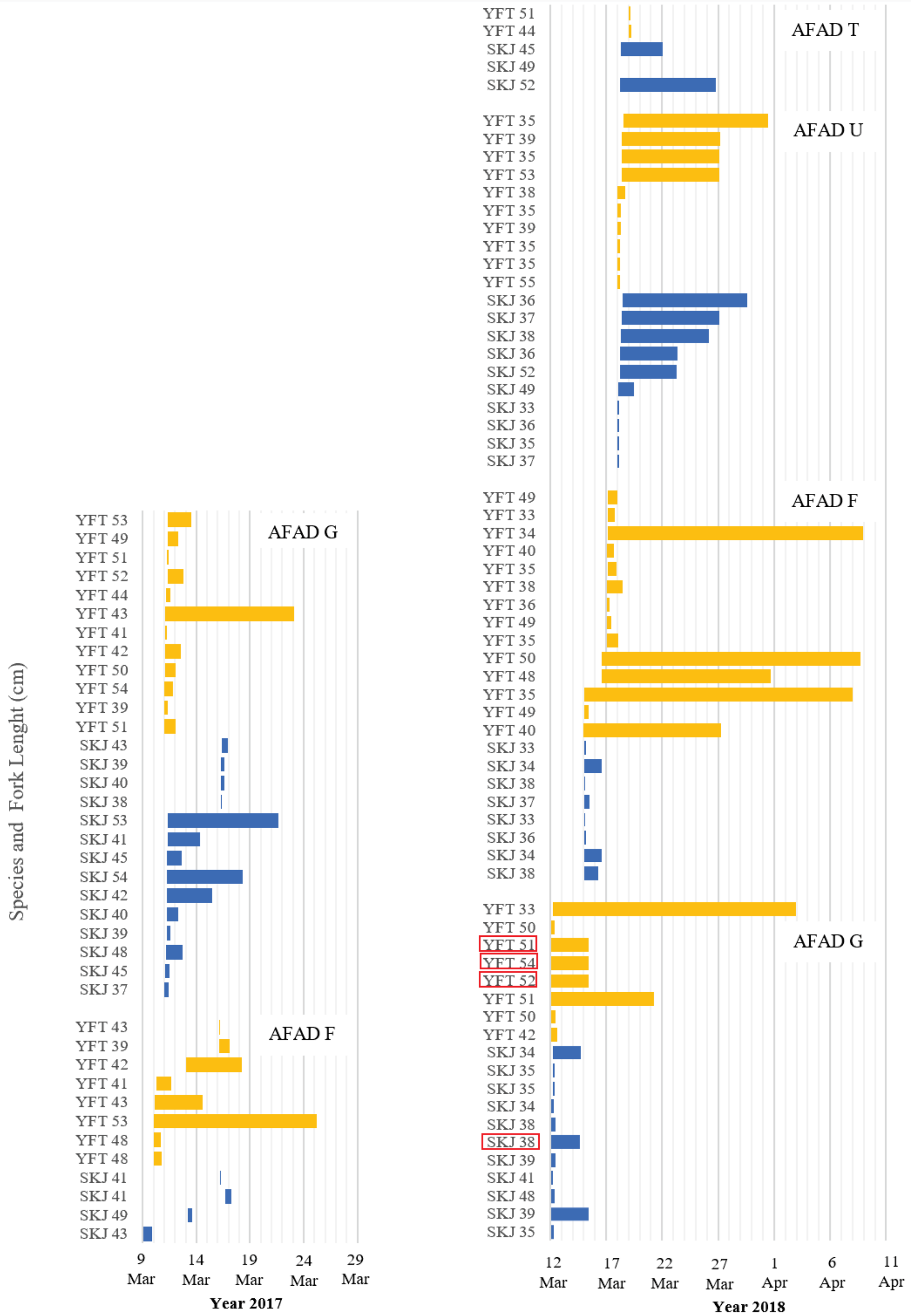

Figure 4.5: First CRTs at tagging AFADs F, G, T and U. (Yellowfin tuna, skipjack tuna, that moved between AFADs).

The mean, maximum and the minimum CRTs for skipjack and yellowfin tuna for each replicate are presented in Table 4. The mean CRT for yellowfin tuna was 2.54 days in 2017 and 5.52 days in 2018, and 4.42 days over the entire study period (2017 and 2018 combined). For skipjack tuna the mean CRT was 1.83 days in 2017 and 2.08 days in 2018, and 2.03 days over the study period.

Table 4.4: The mean, maximum, minimum and standard deviations of the first CRTs, mean fork length and n= number of tunas.

Cohort	Mean CRT (days)	Max CRT (days)	Min CRT (days)	SD CRT	Mean FL (cm)	n
SKJ-AFAD F-2017	0.480	0.88	0.02	0.380	43.50	4
SKJ-AFAD F-2018	0.676	1.57	0.08	0.669	35.37	8
SKJ-AFAD G-2017	2.219	10.34	0.03	3.058	43.14	14
SKJ-AFAD G-2018	0.794	3.44	0.15	1.108	37.82	11
SKJ-AFAD T-2018	4.107	8.50	0.07	4.226	48.67	3
SKJ-AFAD U-2018	4.000	11.11	0.14	4.170	38.90	10
YFT-AFAD F-2017	3.599	15.20	0.04	5.053	44.62	8
YFT-AFAD F-2018	7.396	23.98	0.23	9.806	40.78	14
YFT-AFAD G-2017	1.837	12.01	0.13	3.262	47.42	12
YFT-AFAD G-2018	5.336	21.75	0.34	7.241	47.87	8
YFT-AFAD T-2018	0.215	0.28	0.15	0.092	47.50	2
YFT-AFAD U-2018	4.113	12.94	0.20	5.049	39.90	10
All SKJ 2017	1.83	10.34	0.02	2.779	43.22	18
All SKJ 2018	2.08	11.11	0.07	3.065	38.56	32
All YFT 2017	2.54	15.20	0.04	4.043	46.30	20
All YFT 2018	5.52	23.98	0.15	7.729	42.59	34
All SKJ (2017+2018)	2.03	11.11	0.02	2.93	40.24	50
All YFT (2017+2018)	4.42	23.98	0.04	6.72	43.96	54

The longest recorded CRT were 23.98 days and 11.11 days for yellowfin tuna and skipjack tuna, respectively. The results of the Wilcoxon signed ranked test conducted on CRTs for different cohorts (Table 4) showed no significant differences between different combinations of cohorts except for the comparison of CRTs between skipjack tuna and yellowfin tuna tagged in 2017 and 2018 combined (p-value = 0.03). Test results for other cohorts are included in the appendix.

4 Discussion

4.1 Experimental approach

Following the striking result obtained during the first tuna tagging study within the Maldivian AFAD array (Govinden et al. 2013), where no inter-FAD movement was recorded, our study was designed to test a specific hypothesis initially postulated on the directionality of movements displayed by tuna in the array. The absence of movements observed in the Govinden et al. 2013 had never been observed in other similar studies, when several surrounding FADs were instrumented (Laurent Dagorn et al., 2007; Robert et al., 2013; Rodriguez-Tress et al., 2017). Govinden et al., (2013) suggested that the observed absence of movements between FADs could either be due to the large distances between FADs situated towards the north and the south of the experimental FAD, or, to a non-anticipated easterly/westly movement. In science, hypotheses are usually tested through experiments where one possible explanatory variable is controlled and modified. In the field of FADs and tuna, setting an experiment is quite challenging as (1) tuna live in the pelagic realm where experiments are logistically challenging and (2) AFAD arrays cannot be modified easily. Among the few experiments conducted in this field of research, Robert et al. (2013) conducted an experiment with two pairs of AFADs in the Seychelles specifically deployed to investigate the influence of tuna social behavior in dynamics of aggregations at FADs.

In order to test our hypothesis after Govinden et al. (2013), we needed to work (1) in the same geographical area than Govinden et al. (2013) and (2) instrument an array with AFADs located around the ones where tuna are tagged. Removing or adding AFADs in the Maldives is challenging as it requires approval of the government and fishers and is very costly (USD ~ 15,000 per AFAD). We decided to conduct an experiment in a sub-section of the Maldivian AFAD array, located in the South (Figure 4.1 and 4.3). The main difference from the Govinden et al. (2013) study site is that AFADs were not aligned on a single axis but formed a 2-dimensional array, which allowed to address the hypothesis of a privileged orientation (e.g. east-west or west-east) of tuna movements.

4.2 Directionality of tuna movement

The general trend of tuna movements in the Maldives is considered to be linked to the monsoon seasons – northeast monsoon and southwest monsoon. Conventional tagging experiments conducted in the past showed that during the northeast monsoon when the currents are from east to west tuna tend to move westward while in the southwest monsoon when the current is in the opposite direction fish tend to move eastward (Anderson et al., 1996; Yesaki & Waheed, 1992). Analysis of the conventional tagging data by Yesaki and Waheed (1992) also showed that small skipjack (< 50 cm) are less migratory and tend to stay closer to the Maldives than yellowfin. These tagging experiments also showed that the long-distance migrations were along with the current (westwards during the northeast monsoon and eastwards during southwest monsoon) (Yesaki & Waheed, 1992).

During our study, acoustic tagging was conducted in March (which is towards the end of the northeast monsoon and the beginning of the transition period for the southwest monsoon) and between 2°N and 2°S, where there is less effect from the monsoon currents than in the centre or north of the country (Anderson, 2005a). In addition since the inter-monsoon periods are also characterized by weaker winds and currents it is believed to have less influence on the direction of tuna movements.

In several acoustic tagging experiments conducted at AFADs in other parts of the world, tuna were observed to move between AFADs (Laurent Dagorn et al., 2007; Holland et al., 1990; Mitsunaga, Endo, Anraku, Selorio Jr, & Babaran, 2012; Ohta & Kakuma, 2005; Robert, Dagorn, Deneubourg, Itano, & Holland, 2012; Rodriguez-Tress et al., 2017). In the Maldives, however, such movements were not obvious. For five tagging events, we did not observe any movement, similar to the four tagging events in Govinden et al. (2013). This result indicates that although some characteristics changed between the two FAD sub-arrays that were investigated, results tend to be comparable with no tuna exhibiting inter-AFAD movements in nine tagging events out of ten. The slightly denser AFAD environment in our experiment, with AFADs surrounding those where fish were tagged in several directions, did not contribute to observe movements by tuna from all our tagging events.

Only one tagging event showed some fish visiting other AFADs, with 20% of tagged fish performing inter-AFAD movements. There was no clear directionality in the movements of these individuals as they associated to neighboring AFADs. Hence, these results support the hypothesis of a no directionality in the movements of tuna within the Maldivian FAD array. Rather, it seems that the distances between AFADs can explain the rare observed movements. Perez et al. (2020) observed that when the inter-AFAD distances are shorter (i.e. the AFAD network is denser) tuna tend to spend more time at the AFADs and visit more FADs. Robert et al. (2013) found that tuna behaviour in an array of AFADs is not constant and suggested that it depends on local conditions. Our interpretation is that the average distances between AFADs in the Maldives do not facilitate movements between AFADs, but that some particular environmental conditions could sometimes lead tuna to move between them, as observed for some fish tagged at G AFAD in March 2018. The tagging data from AFAD G in 2018 tend to show that some fish left the AFAD together e.g. some yellowfin tuna seemed to leave the AFAD in one school but did not appear together at the same AFAD. The school most likely split as they left the AFAD and fish moved in different directions.

The higher observed speed in our study between two AFADs (skipjack moving from G to H at 1.57 km/h – Table 4.2) could suggest a more or less directed movement between the two AFADs. Dagorn et al. (2007), using speeds measured during active tracking, considered that a speed faster than 2.5 km/h could correspond to directed movements. However, they worked with tuna that were mainly 70-75 cm FL (mode of their size distribution), while our skipjack was 38 cm FL. When considering body lengths, our skipjack moved at an average speed of 1.15 bl/s, which is higher than the 2.5 km/h threshold from Dagorn et al. (2007), which approximately corresponded to 0.96 bl/s (for a 72.5 cm FL tuna). We could then hypothesize that this skipjack swam directly from FAD G to H, which are 47 km apart. This distance is larger than the longest directed movement observed from the same passive tracking protocol by Dagorn et al. (2007) in Oahu (37 km) and is almost three times longer than the maximum orientation distance (17 km) suggested by Girard et al (2004) from active tracking studies.

Only some fish from the same tagging replicate visited several AFADs. This result is in agreement with Robert et al. (2013) who considered that the behaviour of tuna at AFADs was likely dependent upon local conditions around the AFAD at a given time, either environmental factors or social interactions. After Govinden et al. (2013) and our study, it seems that most of the time, tuna in the Maldives only visit one AFAD, but some particular conditions (e.g. those at AFAD G in March 2018) could lead some tuna to stay longer within the AFAD array and visit more AFADs. Our study strongly suggests that the AFADs in the Maldives do not act as a network but as independent attractors.

4.3 Continuous residence time

In a study with similar fish sizes, Robert et al. (2012) observed a mean CRT of 4.0 days for yellowfin tuna <50 cm which is comparable to what we observed, both 2017 and 2018 combined (4.42 days), but our values were much higher than what was observed during Govinden et al. (2013) – mean 0.66 days. However, we did observe some differences between the years in our study. The mean CRT observed for yellowfin tuna in 2018 (mean 5.52 days) was more than twice that of 2017 (mean 2.54 days). In the 2009 study (Govinden et al., 2013) the mean CRTs observed for skipjack for the two tagging replicates were 3.5 days and 0.2 days (no data available for the whole dataset in this paper), while we measured a mean CRT of 2.03 days (2017 and 2018 combined). Our values are comparable to what was found by Rodriguez-Tress et al. (2017) in Mauritius (mean 2.5 days).

5 Conclusion

When combining all acoustic tagging conducted on yellowfin and skipjack tuna around AFADs in the Maldives (Govinden et al. 2013 and this study), for 9 of the 10 tagging replicates, no tagged tuna visited another AFAD. The only tuna that visited several AFADs did not display any clear pattern in directionality within the array. The results seem to suggest that (1) there is no particular directionality in the movements of tuna within the AFAD array, (2) the rather large AFAD distances in the Maldives do not favour movements between AFADs. Each AFAD within the array seems to act as an individual AFAD with no or little influence by other AFADs. Therefore, the AFAD array in the Maldives does not seem to act as a network, i.e. AFADs are poorly connected (from a tuna point of view). Thus, FADs in the Maldives, with large inter-AFAD distances, could be considered to have little effect on the movement behavior of tuna but at the same time, still help fishers to access tuna more easily. Results from this study also provide useful knowledge for management plans of AFADs in other countries or management plans of drifting FADs (purse seine fleets) with the objective of maintaining the role of fishing tools of FADs while minimizing possible effects on movement behavior of tuna, in order to avoid any risk of ecological trap (L Dagorn et al., 2013; Hallier & Gaertner, 2008).

Appendix


Significant p−values (<0.0014)
YFT_U_2018 0.155 0.907 0.438 0.496 0.696 0.138 0.974 0.307 1
YFT_G_2018 0.031 0.206 0.013 0.625 0.958 0.973 0.165 1 0.307
YFT_G_2017 0.343 0.877 0.218 0.644 0.521 0.374 1 0.165 0.974
YFT_F_2018 0.07 0.27 0.004 0.364 1 1 0.374 0.973 0.138
YFT_F_2017 0.195 0.441 0.041 0.894 1 1 0.521 0.958 0.696
SKJ_U_2018 0.131 0.703 0.418 1 0.894 0.364 0.644 0.625 0.496
SKJ_G_2018 0.657 0.132 1 0.418 0.041 0.004 0.218 0.013 0.438
SKJ_G_2017 0.238 1 0.132 0.703 0.441 0.27 0.877 0.206 0.907
SKJ_F_2018 1 0.238 0.657 0.131 0.195 0.07 0.343 0.031 0.155
SKJ_F_2018
SKJ_G_2017
SKJ_G_2018
SKJ_U_2018
YFT_F_2017
YFT_F_2018
YFT_G_2017
YFT_G_2018
YFT_U_2018
p.value < 0.05/36
FALSE

General discussion

Overview and synthesis

The lack of natural resources in the Maldives have limited the economic activities which provide a sustainable income for the inhabitants – especially for those small island communities (<1000 people per island). This tuna fishery is of prime importance to the Maldives. It has provided sustenance to all people living in the archipelago. It has provided a cheap source of protein and opportunity for employment in the island communities. It has been the main export for several decades.

In the last 50 years the Maldives tuna fishery has evolved from a traditional subsistence fishery to a more commercial fishery harvesting for export. The tuna fishing vessels have developed from a small (12 m) wooden vessel powered by sail to a large (30 m) fiberglass vessel with a 600 hp engine. The average number of crew members working on a vessel has also increased from 10 to 25 fishers. Their average range of operation has expanded from 24 km to 120 km offshore, with many vessels conducting multiday trips instead of single day trips. Now fishing vessels use modern technology (e.g., geostationary binoculars, bird radars, echosounders), which facilitates their at-sea operations, but also increases the operational costs. In addition, since the 1980s', Maldivian fishers can use AFADs which help them find and catch tuna. All these changes during the last few decades have contributed significantly to the annual tuna catches of the Maldives – increased from 33,000 tons in 1970 to more than 100,000 tons in the recent years.

The expansion and the development of tuna fishery in the broader Indian Ocean and in the Maldives, legitimately raises the question of sustainability of the Maldivian tuna fishery. In this context it was important to describe the Maldivian tuna fishery, review and understand the role of AFADs in the fishing strategy and performance of the Maldivian pole and line fishery. In addition, it was also crucial to acquire knowledge on the behavioral ecology of tuna, both skipjack and yellowfin tuna (the two most frequently caught species in the Maldives), in the Maldivian AFAD array and examine whether this low-density AFAD array is an asset or a liability for the sustainability of the fishery. Moreover, it was important from the beginning of this work to involve fishers in the research process. Collecting fishers' knowledge is an efficient method to improve our knowledge on the ecology of fish, and also contributes to engage fishers in research. During this study, a significant effort was made to gather field data as well as knowledge from fishers that could help better understand the ecology of tuna within the AFAD array. Data were collected through fisher interviews (54) and acoustic tagging (SKJ = 65 and YFT = 57) through the instrumentation of 21 AFADs using VR2 acoustic receivers.

One of the most critical initiative by the Maldivian government to support its tuna fishery was deploying and constantly maintaining an array of 55 AFADs. The association of fish with drifting floating objects was long known by Maldivian fishers and fishing around floating objects was common among the fishers of Southeast Asia (T Dempster & Taquet, 2004). Hence these efforts began in the Maldives in the 1980s to increase the catchability of tuna by deploying AFADs. Today it is one of the largest AFAD arrays in the Indian Ocean exclusively managed by the government. Considering the extent of the Maldivian archipelago, these 55 AFADs generate a low-density AFAD array as compared to AFAD arrays in other countries, e.g. Mauritius (Rodriguez-Tress et al., 2017), Indonesia (Widodo et al., 2020) and Hawaii (USA) (Pérez et al., 2020) in the Pacific Ocean. Despite this relatively low-density AFAD array, the Maldivian tuna fishery catches on average a hundred thousand tons of tuna per year, making the country one of the leading tuna fishing nations in the Indian Ocean. This is mainly due to a high abundance of tuna in the Maldivian waters and the size of the fleet, which is formed by a very large number (nearly 1000) of small to medium size pole and line, and handline vessels. This corresponds to a significant fishing effort. These pole and line vessels exploit tuna associated to AFADs, but also tuna in free-swimming schools, schools associated to drifting floating objects passing through the Maldives waters, and schools associated to seamounts located in the EEZ.

AFADs help fishers by reducing the search cost and increasing the catchability. The fishing success therefore depends, at least partially, on the time tuna stay around single AFADs, but also on the total time they spend in the AFAD array. Measuring how much time tuna stay at AFADs is an important knowledge to understand tuna dynamics, as well as their availability to fishing. We found that both skipjack and yellowfin tuna in the Maldives AFAD array stay associated with AFADs for a relatively short period (few days). This information, obtained from electronic tagging (Chapter 4), corroborates with information shared by fishers (Chapter 3), indicating another example that fishers knowledge can be used to better understand the behavior of fish. These values were also comparable with those collected in other countries, e.g. Rodriguez-Tress et al. (2017) and Robert et al. (2012). Some differences were found when compared with the first electronic tagging experiment in the Maldives (Govinden et al. 2013), which argues for more tagging experiments in order to better understand the associative behavior of tuna in the Maldivian AFAD array.

In addition, there was almost no inter-AFAD movement of tuna observed, similarly to what was found by Govinden et al. (2013). Thus, the total residence time of tuna within the AFAD array appear to be short, limited to the single AFAD usually visited by individual tuna. Our study has shown that at present, with such wide inter-AFAD distances, there is very little connectivity between the AFADs, thus the 55 AFADs around the Maldives do not act like a network of AFADs. It could be hypothesised that increasing the number of AFADs could then increase the total time fish spend associated to AFADs, making them more accessible to fishing (see Pérez et al., 2020). According to the findings by Pérez et al., (2020), increasing the AFAD density should increase the connectivity between AFADs thus tuna should visit more AFADs and spends less time unassociated. In the Maldives, this can result in tuna spending more time in the AFAD array. A dedicated study conducted over a small portion of the Maldivian array, where a set of AFADs are deployed around an existing AFAD (Figure 5.1), may help validating this hypothesis. The protocol consists in deploying 6 new AFADs around an existing one, thus creating a “flower” array with a high local density of AFADs. Tagging fish at the centre of this experimental array would allow us verifying whether fish visit more AFADs, and the time they spend at AFADs and in this “flower” array.

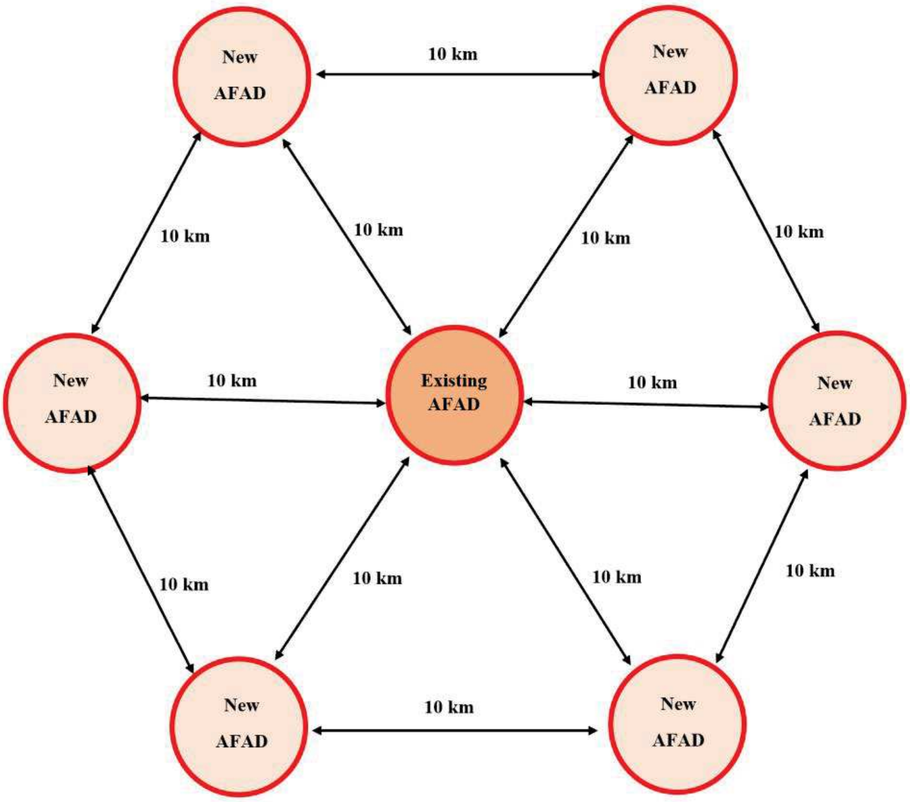

Figure 5.1: A set of 6 AFADs deployed around an existing AFAD to observe the movement of tuna within this array (proposed future study).

On the other hand, too many AFADs could question the sustainability of the fishery on the long term, similar to drifting AFADs. Reducing the inter-AFAD distances and increasing the density of the AFAD array would likely help retain the tuna longer in these waters, increasing the catchability. At the same time, increasing overall catches at AFADs can also result in an increase in catches of juvenile yellowfin tuna which may have a negative impact on the yellowfin tuna stocks in the Indian Ocean, considering that the yellowfin tuna stock in the Indian Ocean is overfished and subject to overfishing (ISSF, 2021). At the same time, increasing catches provides benefits for the country. It may increase the earnings for the fishers by creating more opportunities for private parties to process the fish thus attracting more youth to the fishery. But on the other hand, it can also put more pressure on the government company, MIFCO, to purchase the fish. Even at present the company is struggling to buy all the fish landed by the fishers.

The choice by the Maldivian government for a low-density AFAD array could appear quite unique in a world where the standards are more towards large numbers of AFADs. Our study allowed to investigate the role of AFADs in the strategy and the performance of the Maldivian pole and line fishery in order to examine the pros and cons of low-density AFAD arrays. When setting AFAD arrays, the number of AFADs, as well as the distances between them, represent key questions, as they could have direct impacts in terms of cost, fishing strategies, catches, as well as relationships between fishers. In terms of tuna behavior, the number of AFADs could have direct effects on their movements. The total biomass of fish associated to AFADs depends on the local fish population but also on the FAD density (Capello et al., 2016). Consequently, the number of AFADs is likely to play a role on the proportion of fish that is not associated to floating objects, e.g., in free-swimming schools. As fishers usually exploit tuna in different types of schools, the number of AFADs should have an effect on the relative number of schools of each different type (AFAD, drifting floating objects, free-swimming schools) thus affecting the fishing strategy, e.g., the distribution of the fishing effort among the different school types.

Obviously, it is important to gather more information in order to help the Maldives to develop science-based management of their pole and line fishery. The sustainability of the fishery, as any other human activities depends on the three pillars:

- Environmental or ecological, e.g., the status of the tuna stocks and oceanic ecosystems in the Indian Ocean,

- Social, e.g., employment of the population, employment for youth and women
- Economics, e.g., economic viability of the fishery and all the associated components, from shipyard to markets

Continuing the effort of this thesis to improve our understanding of the biology and ecology of tuna in the Maldives should be promoted. During the thesis, only data from fishers' interviews and electronic tagging were presented, analyzed and discussed. However, in addition to this, more data were collected within the framework of this thesis, which could not be analyzed due to a lack of time:

- Measures of bioelectrical impedance analysis (BIA) were taken from 792 skipjack tuna to examine the body composition of tuna caught from AFADs, DFADs, log associated schools and free-swimming schools.

- A total of 1898 tuna (1529 skipjack and 369 yellowfin tuna) were tagged with conventional tags at free swimming schools, AFADs and drifting objects (DFADs and logs). All conventional tagging was carried out on a pole and line fishing vessel between 9th March and 26th April in 2017 and 12th March and 12th September 2018.

- Echo-sounder buoys were attached to the 21 AFADs instrumented with acoustic receivers (for acoustic tagging, Chapter 4) and collected data for a period of 5 months in 2017 and 8 months in 2018, simultaneously to the electronic tagging.

Conventional tagging data gathered during this study can be used to analyze the movements and interactions between the different school types (e.g. free-swimming schools, DFADs, logs, AFADs, sea-mounts) for tuna that pass through the Maldives. Investigating the mixing between the different types of schools could help understand how tuna use the different aggregating points (AFADs, DFADs, logs, seamounts) in the Maldivian EEZ and how much the fishery also depends on them. The model by Pérez (2021), coupled to this data, could provide the bases for a future study that would investigate the effects of different numbers of DFADs passing through the Maldives on tuna behavior, including the distribution of tuna among the different school types.

Since echosounder data were collected during the acoustic tagging experiment, it may be possible to further study the departure behavior of tuna from individual AFADs. In particular, comparing data from individuals (tagging) and from aggregations (echosouder) would help understanding the interplay between individual and collective behavior and better understand the dynamics of tuna aggregations at AFADs. As the subarray of 21 AFADs was equipped with echosounders, the data may also be used to analyze the aggregation patterns at the scale of the array. In particular, it could help investigating fishers' knowledge who reported that associations at some AFADs are more frequent and larger and tend to stay longer too. Our tagging work has shown that AFADs in the Maldives seem to be independent. Analyzing the presence / absence of tuna at AFADs from echosounder buoys would help understand the dynamics of tuna within the array, and also investigate the possible roles of local conditions (see Robert et al. 2013). This would be possible thanks to Baidai et al., (2020) who developed a method to determine the presence / absence of tuna at FADs from echosounder buoys. Till now there has not been a study conducted using echosounder data on tuna aggregations at a large array of AFADs. By comparing the aggregations in an AFAD array, it would be possible to identify whether some AFADs are often more productive than others, whether tuna arrive or leave the array at the same time, etc.

Conclusion

The Maldives have an EEZ of around 900, 000 square kilometres. Almost 85% of the tuna fishing activities take place close to the coast within 200, 000 square kilometres. Hence about 80% of the Maldives EEZ is hardly utilized for fishing. Prior to July 2019 some amount of longline fishing targeting bigeye, large yellowfin and sword fish took place in the outer EEZ beyond 75 miles. This limited use of the EEZ is not due to the establishment of official Marine Protected Area (MPA) by the Maldivian government, but by the type of fishing in this country. But in fact, this corresponds practically to the establishment of an MPA which could cover about 80% of the EEZ. This particularity deserves to be studied. Would it be in the interest of the Maldives to exploit a larger part of its EEZ, or on the contrary, should it not remain in a relatively small exploitation area? The consequences in ecological, social and economic terms of maintaining this type of spatial exploitation, or on the contrary of an extension of this zone, should be studied.

Although the tourism sector provides the main source of income for the country (GDP contribution in 2019 was 66.1%) it only employs about 21, 000 Maldivians (NBS, 2020) over a total population of 450,000. A similar number of people work as active fishers on the fishing vessels but the majority of whom are above 35 years old. The lack of interest among the youth in the tuna fishery questions the sustainability of the Maldives tuna fishery. It is hoped that a better understanding of the tuna fishery through research activities such as these would help initiatives that could encourage more to engage in the tuna fishery.

A better understanding of the Maldivian fishery is obviously useful and necessary to assist the government in establishing its fisheries management measures, but also the IOTC in the general Indian Ocean framework. It is important to emphasize that research on the Maldivian fishery also have a much broader interest worldwide. Very few pole and line fisheries have been successful in sustaining themselves. The majority of AFAD arrays, whatever the type of fishing gear, have higher densities. In this sense, the case of the Maldives appears to be almost unique in the world of pole and line fisheries and/or AFAD fisheries. A better understanding of this fishery can thus help many countries that have a pole and line fishery, or that exploit a FAD array, including drifting FADs. The issue of drifting FAD management is at the heart of all RFMOs due to the very high numbers of DFADs used by purse seiners. The Maldives shows that working with a small number of AFADs, managed by a centralized organisation and accessible by the entire fleet, can be a sustainable practice which should be examined as a possible solution to manage DFADs.

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